

Gaseous Controls

Chapter 7: NO_X Controls

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Chapter 7: NO_X Controls
Objective

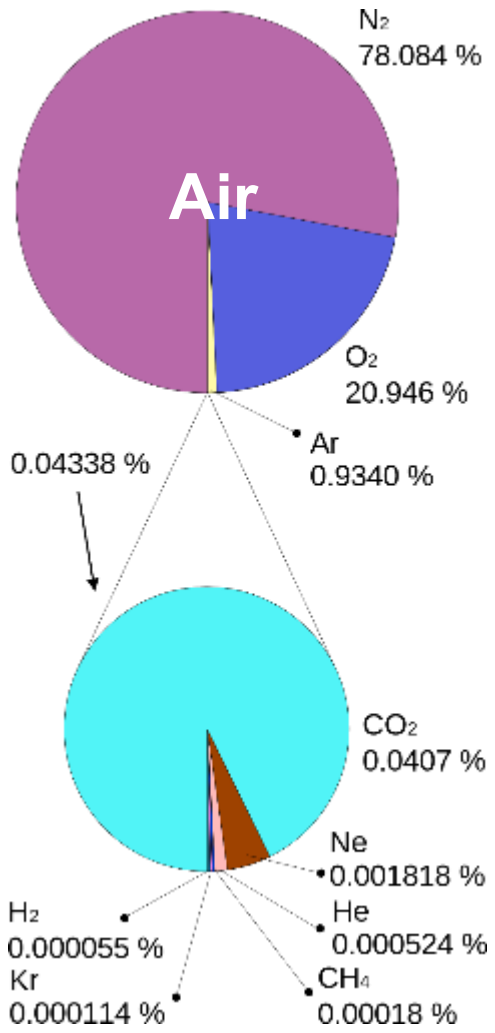
In this chapter, we will discuss:

- How do NO_X control technologies operate?
- What are common types of NO_X control technologies?
- How are NO_X control technologies designed?
- What is the typical control efficiency for NO_X control?
- How are NO_X control technologies monitored?
- What are common problems with NO_X control technologies?
- How do we ensure compliance?

NO_X Formation from Combustion

- NO_X is formed when things burn (>2,370ºF)
  - Nitrogen is oxidized by oxygen resulting in NO_X
  - Side effect during combustion (N_2 is present in air)
  - Air contains ~78% N_2
- NO_X is formed from combination of N_2 & O_2
  - $N_2 + O_2 + \text{energy} \rightarrow 2NO$

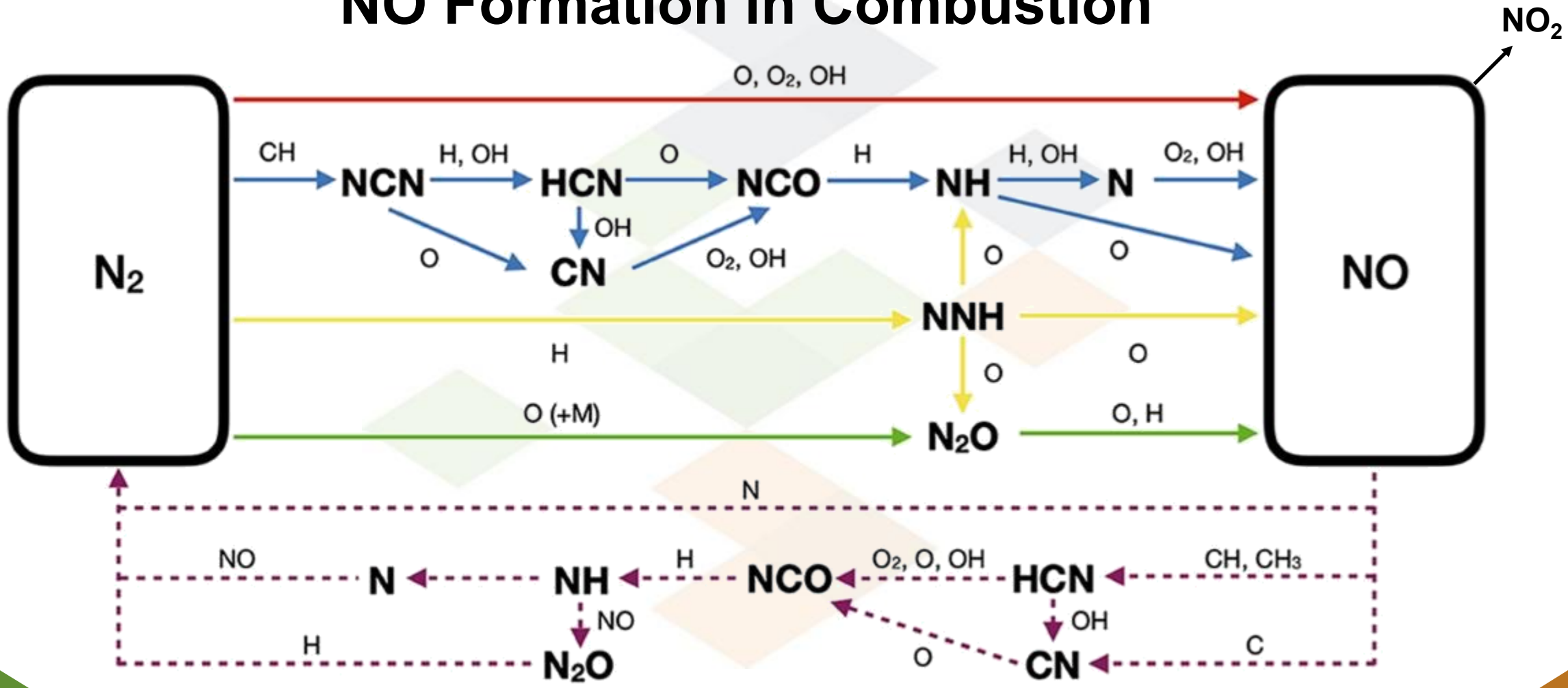
    95% of NO_X starts as NO but quickly oxidizes into NO_2
  - $2NO + O_2 \rightarrow 2NO_2$
  - $NO + O_3 \rightarrow NO_2 + O_2$



NO_X Formation from Combustion

1. **Thermal NO_X:** Airborne nitrogen is oxidized
   - Temperature dependent (increasing temperature increases NO_X)
2. **Fuel NO_X:** Nitrogen in fuel is oxidized
   - Approximately half of fuel nitrogen forms NO_X
   - Nitrogen removed from fuels at refinery (in desulfurization); however, pre-heating heavy fuel oils (#6) increases nitrogen concentration
3. **Prompt NO_X:** Airborne nitrogen oxidized by hydrocarbon radicals in fuel during early combustion
   - Not temperature dependent (no relation between temperature & NO_X)
   - Most combustion generates <10 ppm NO_X from prompt formation

NO Formation in Combustion



NO_X Formation from Combustion

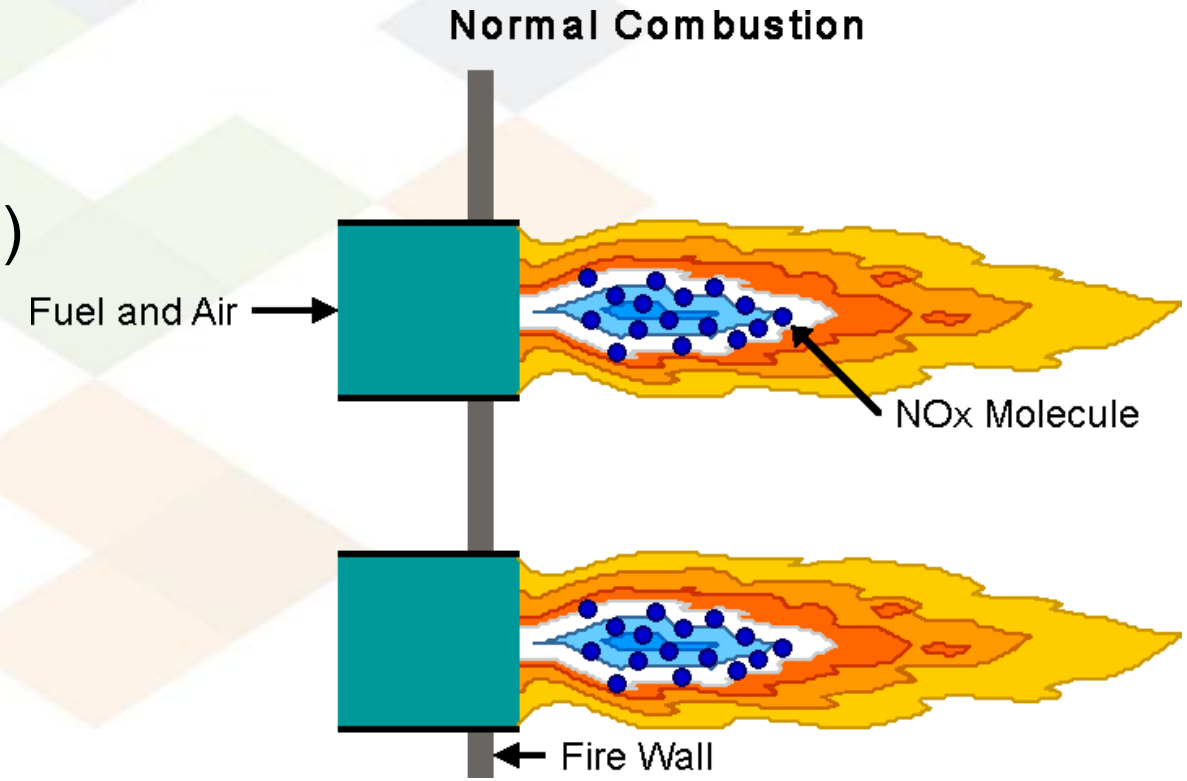
1. **<u>Thermal NO_X</u>:** Greatest source of NO_X for treated fuels, processed to remove organic nitrogen
   - Natural gas & light oils
   - Zeldovich Mechanism for oxidation of nitrogen
     - $N_2 + O \leftrightarrow NO + N$
     - $N + O_2 \leftrightarrow NO + O$
     - $N + OH \leftrightarrow NO + H$ (extended Zeldovich Mechanism for lean fuel conditions)
2. **<u>Fuel NO_X</u>:** Greatest source of NO_X for untreated fuels, from organic nitrogen present in fuel
   - Coal and heavy fuel oils

NO_X Prevention Controls: Interfere with the 3Ts of combustion

- **Time, Temperature, and Turbulence**
  - Increase 3T's = more CO_2 and **NO_X**, less CO and VOC
  - Decrease 3T's = more CO and VOC, less CO_2 and **NO_X**
- Reduce oxygen concentration at peak flame **temperature**
  - Reduce peak flame temperatures (<2,400°F)
  - Less oxygen available to convert N_2 into NO_X
- Reduce residence **time** at peak temperature
- Decrease heat release rate (energy produced)

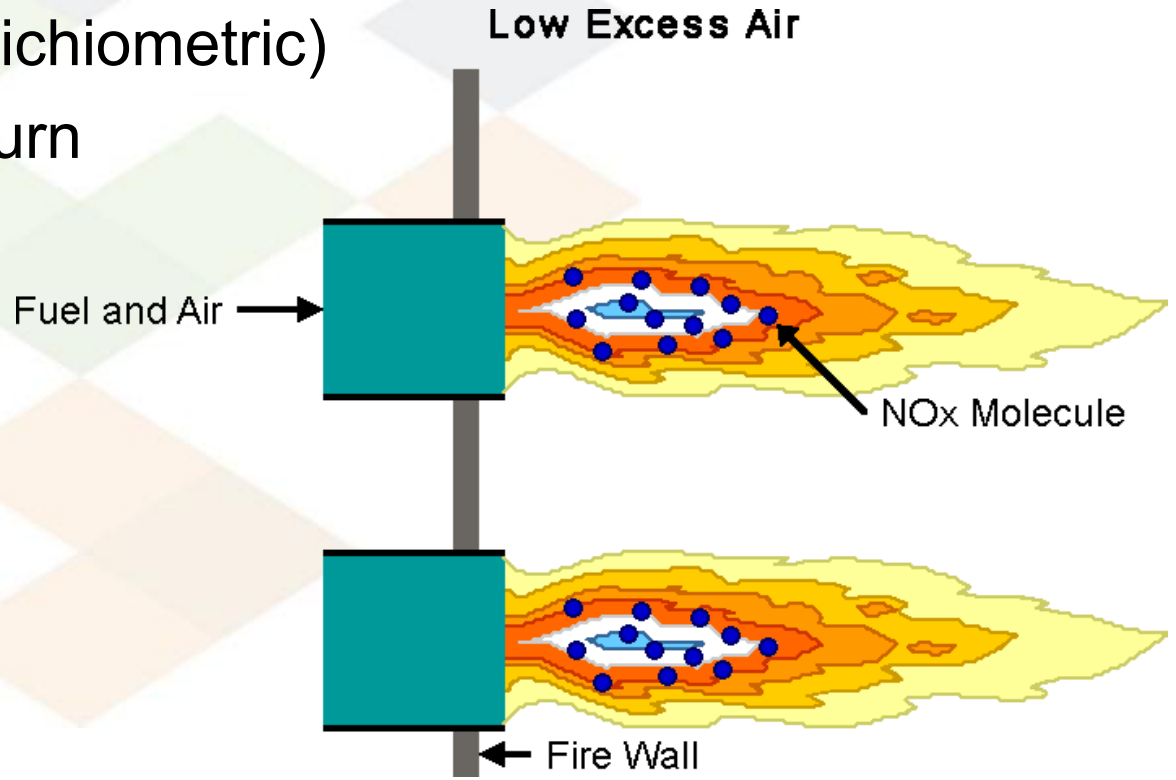
NO_X Controls: Combustion (Burners)

- NO_X is formed from oxidation of nitrogen in combustion air, so reducing combustion air or temperature reduces NO_X
  - Low excess air (LEA)
  - Excess Air Control
  - Burners Out-of-Service (BOOS)
  - Overfire Air (OFA)
  - Staged Combustion
  - Low NO_X Burner (LNB)
  - Flue Gas Recirculation (FGR)
  - Ultra Low NO_X Burner (ULNB)



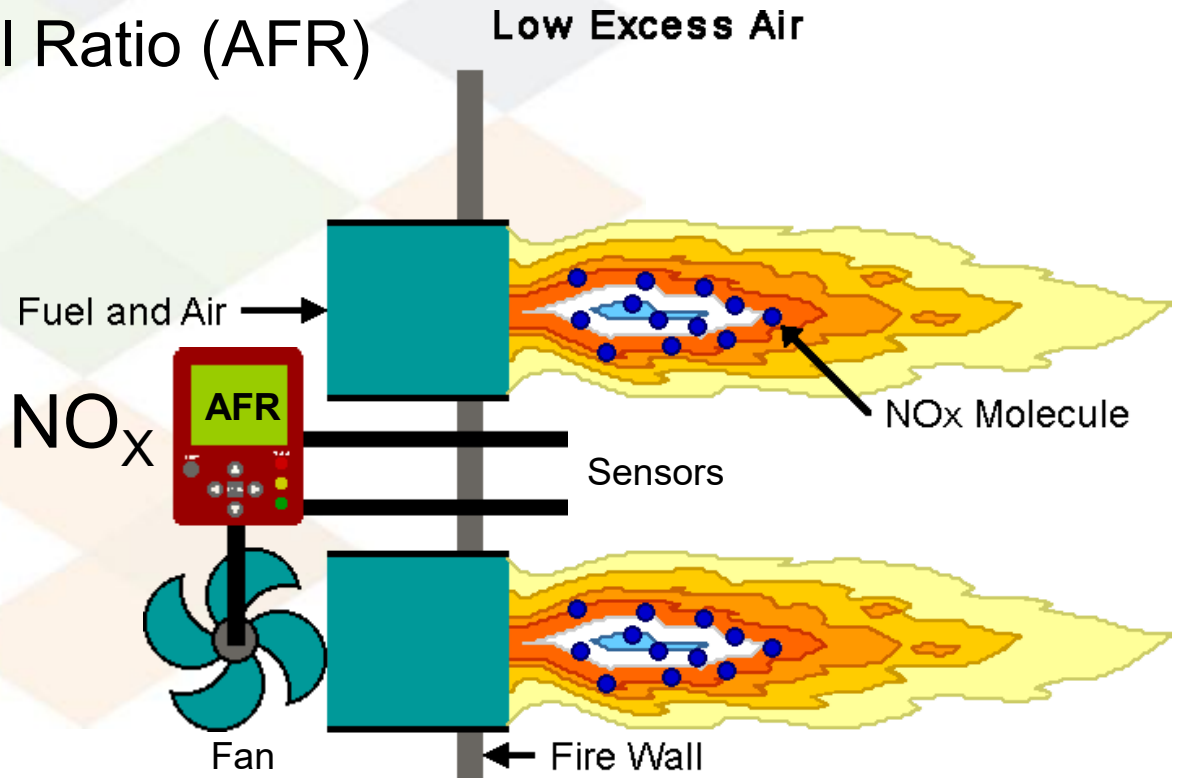
Low Excess Air (LEA)

- Reducing excess air (rich burn) reduces flame temperature and amount of nitrogen available for oxidation to NO_X
  - Lower A/F Ratio closer to 1 (stoichiometric)
  - Moving from lean burn to rich burn



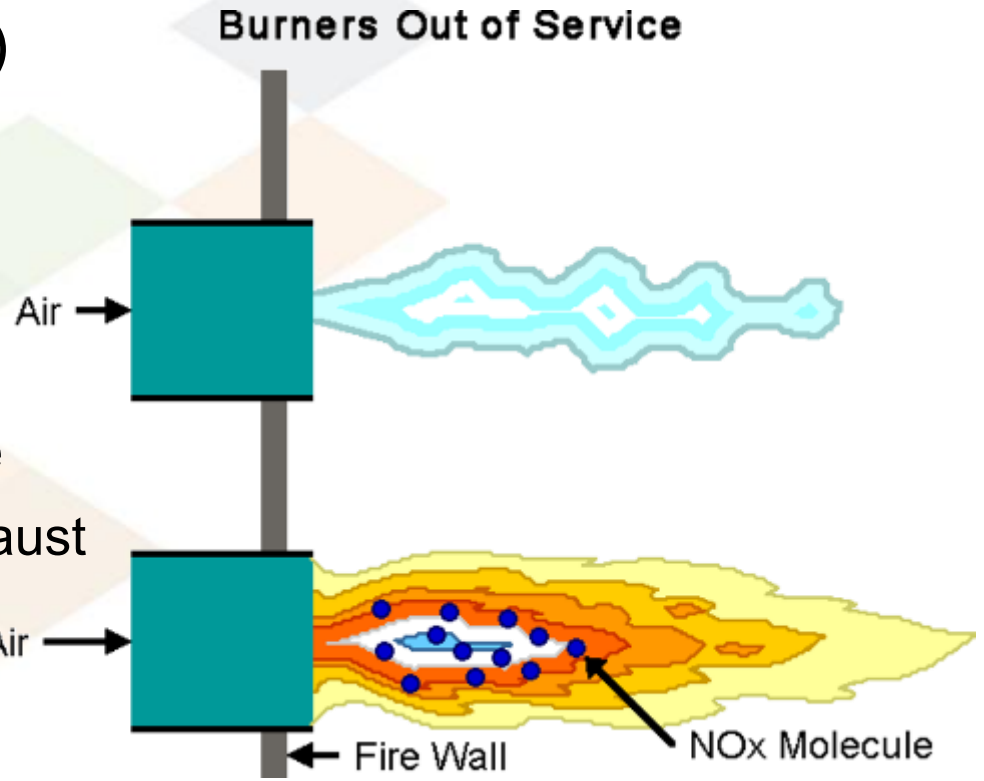
Excess Air Control

- Need equipment to monitor O_2 and temperature in exhaust gas to ensure burners are operating with optimal flame
  - Computer Controller for Air/Fuel Ratio (AFR)
  - O_2 sensors
  - Thermometer
  - Variable Speed Fan
- Minimum excess air = lower NO_X

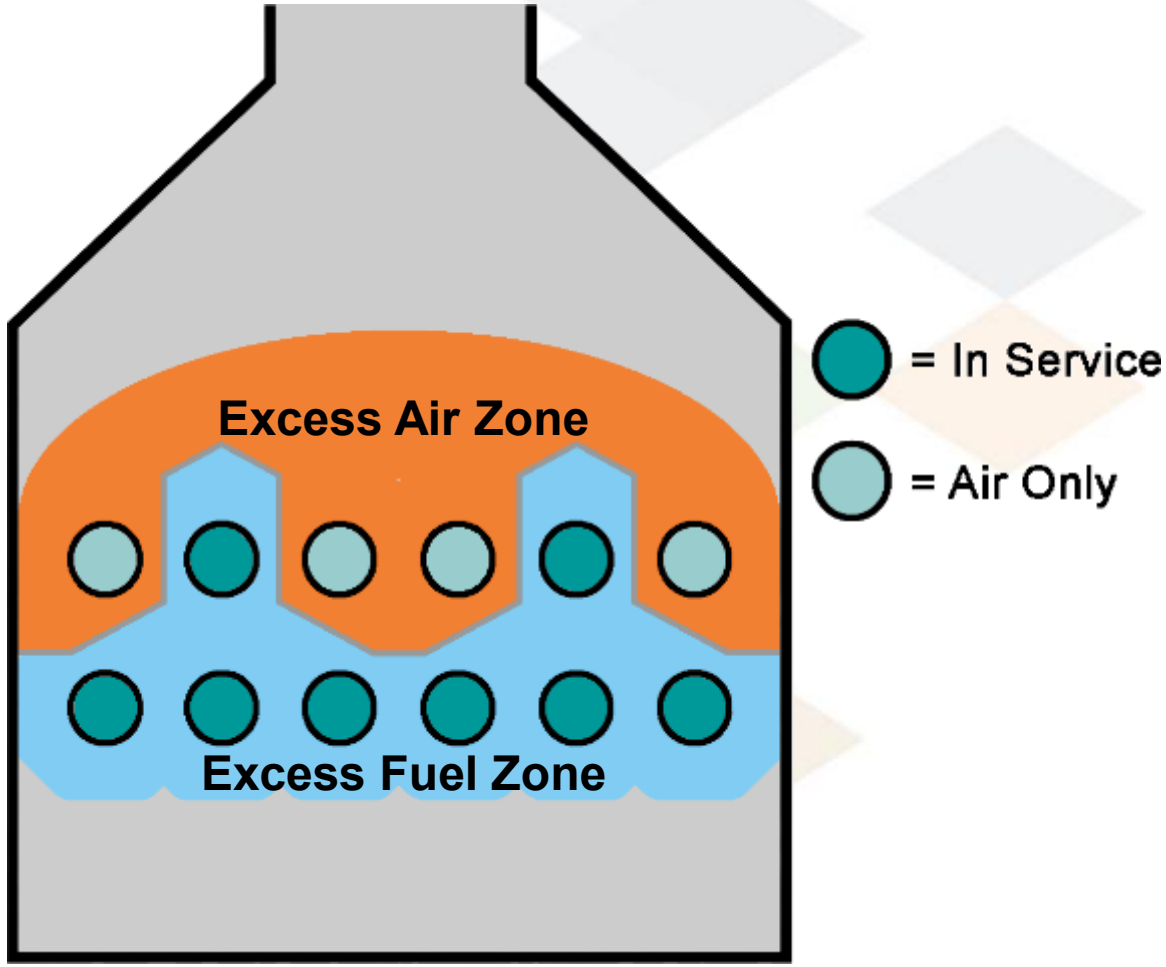


Burners Out of Service (BOOS)

- Cooling flame temperature and reducing number of burners reduces amount of nitrogen available for oxidation to NO_X
  - Fuel-rich and fuel-lean zones (staging)
  - NO_X reduction dependent on number of BOOS
    - Burners may need to return to service during periods of increased demand
  - BOOS pattern defines excess air zone
    - Must be between excess fuel zone and exhaust

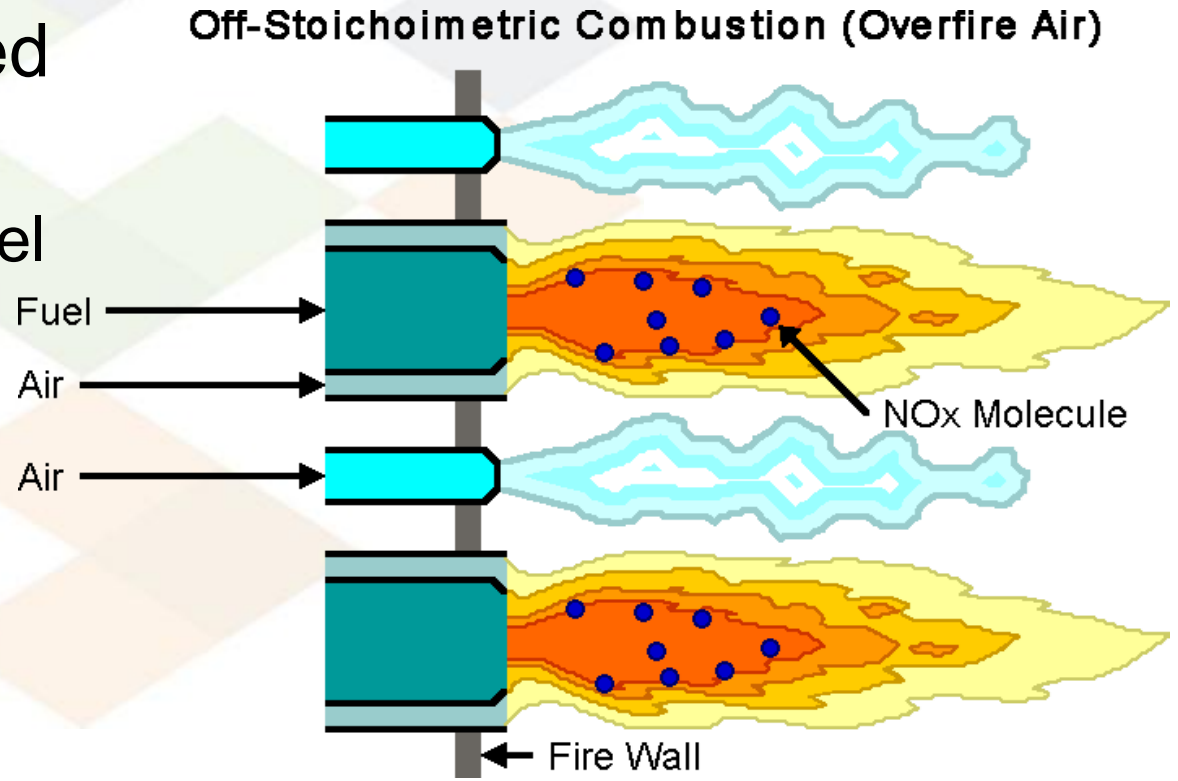


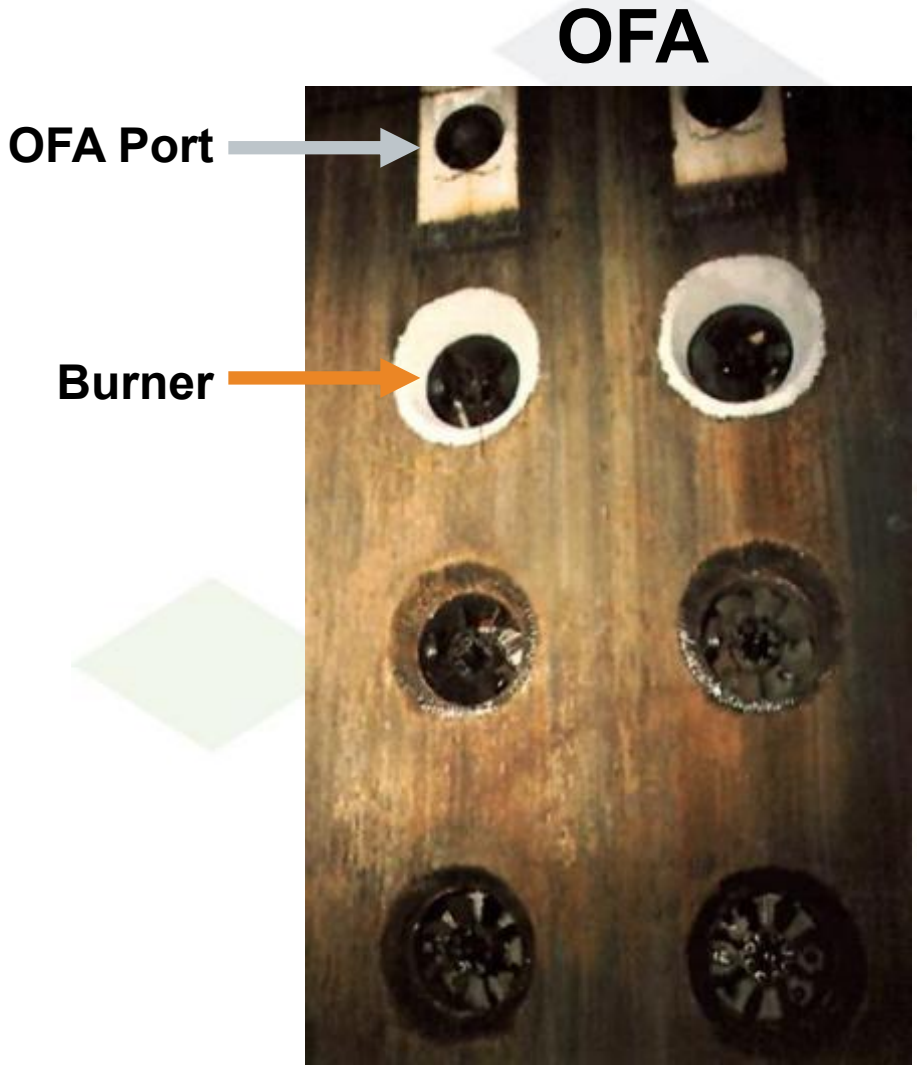
BOOS Pattern



Overfire Air (OFA)

- Portion of combustion air is introduced above main burner zone through dedicated OFA ports
- Some combustion air diverted to create rich-burn fuel zone
  - Combustion air is mixed with fuel in excess burn / lean air zone
  - OFA creates excess air zone to finalize combustion at a lower temperature

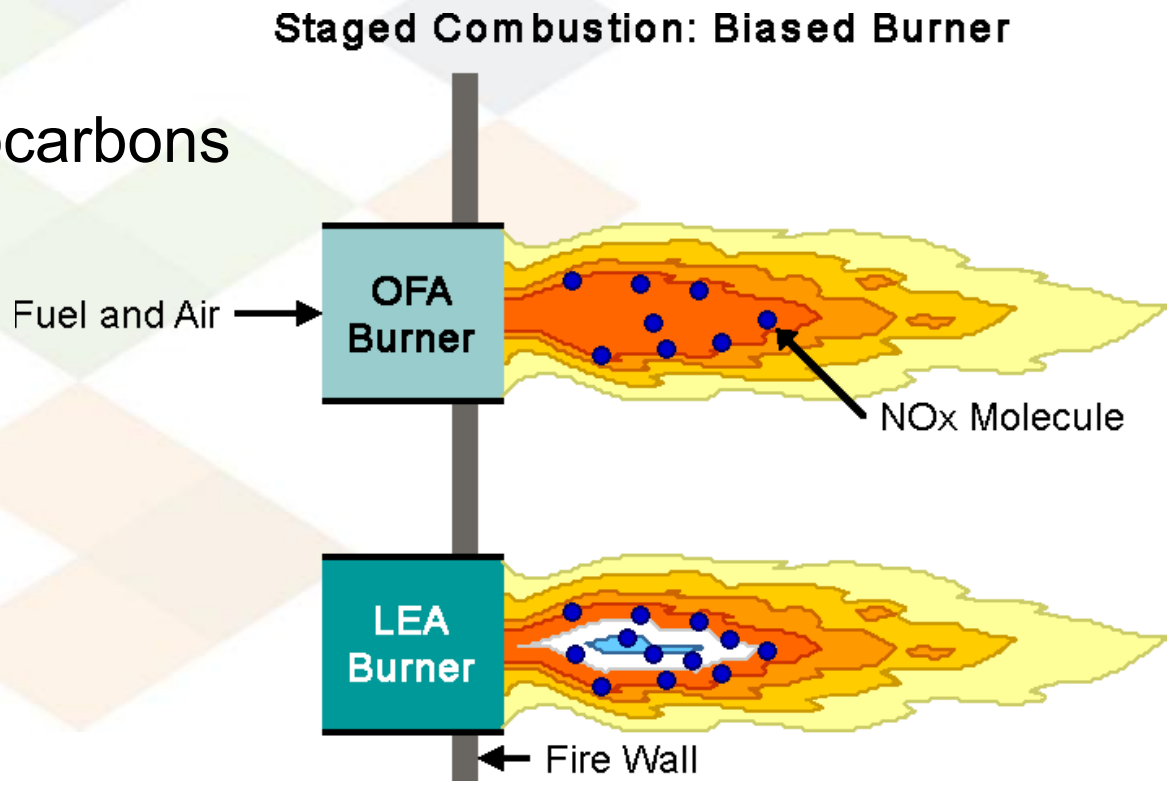



OFA
OFA Port
Burner

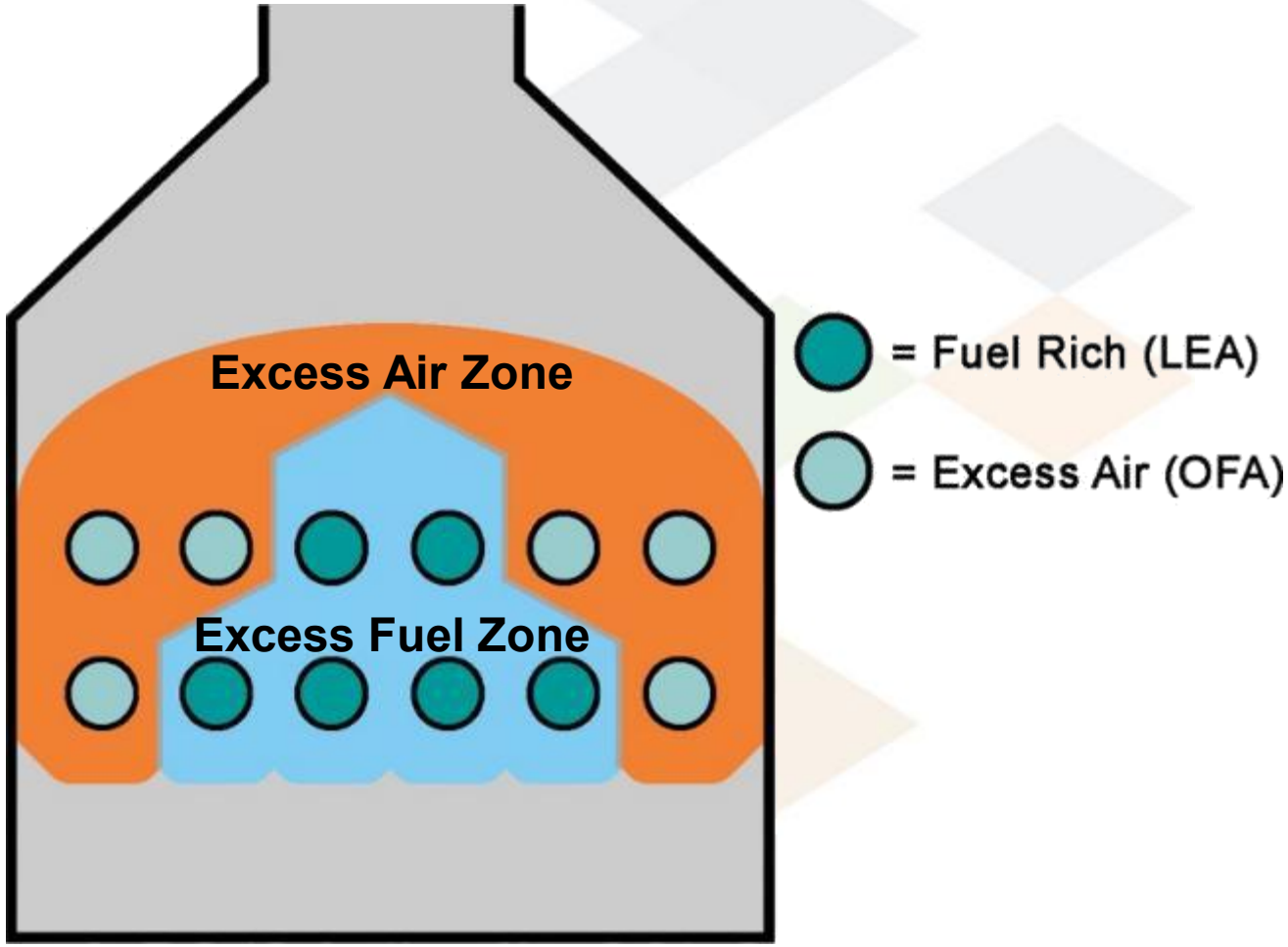
Staged Combustion: Biased Burner Firing

- Intentionally firing different burners as LEA and OFA

1. Fuel-lean zone with OFA
   - Excess air combustion assists with removal of unburned hydrocarbons
2. Fuel-rich burners with LEA
   - Reducing excess air in the combustion zone reduces NO_X



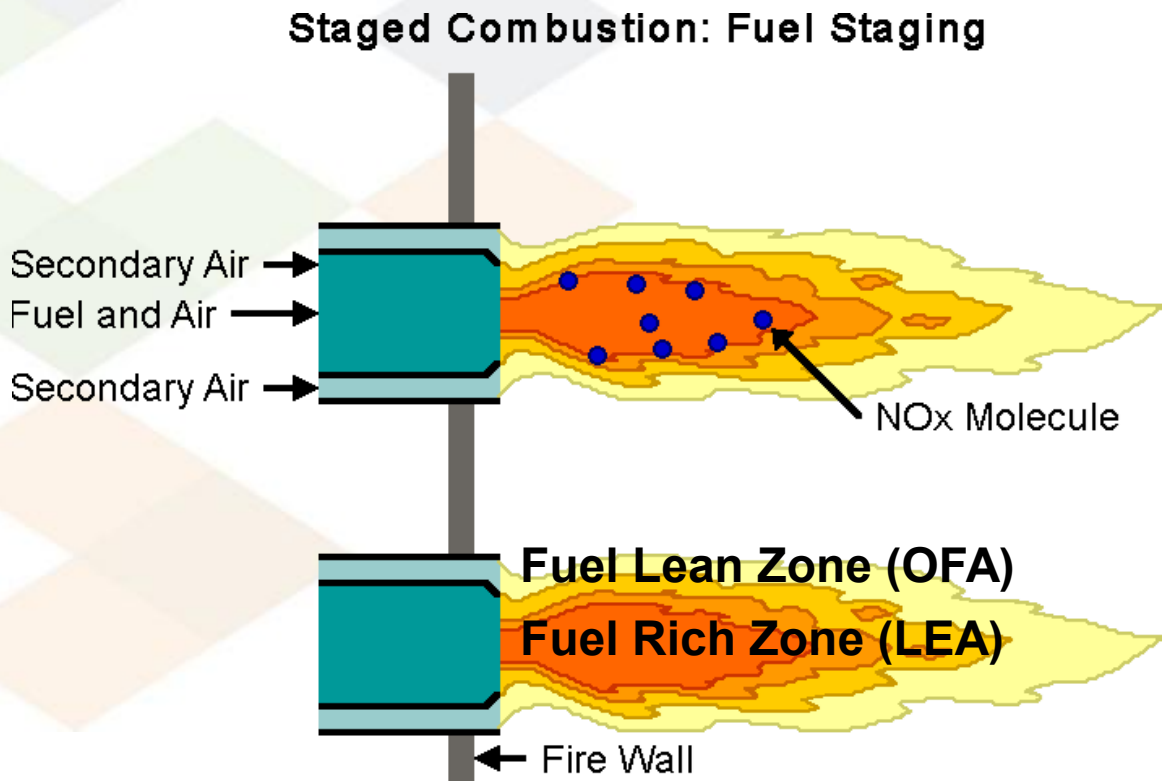
Staged Combustion : Biased Burners



Staged Combustion: Fuel Staging

- Create multiple combustion zones within burner

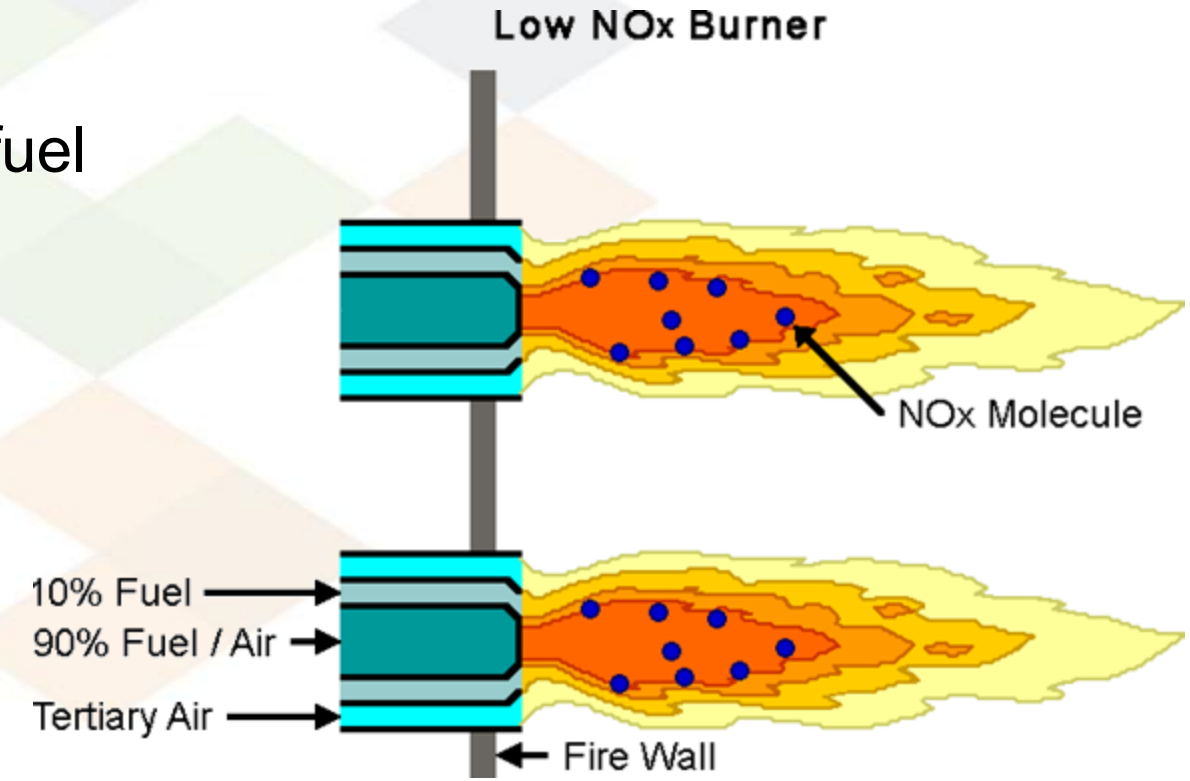
1. Fuel-rich Zone (LEA)
   - Reducing excess air in primary combustion zone reduces NO_X
2. Fuel-lean Zone (OFA)
   - Adding more air above flame allows combustion to finish at a lower temperature



Low NO_X Burner (LNB)

- Multistage combustion completely combusts fuel at lowest temperature (staged combustion within burner)

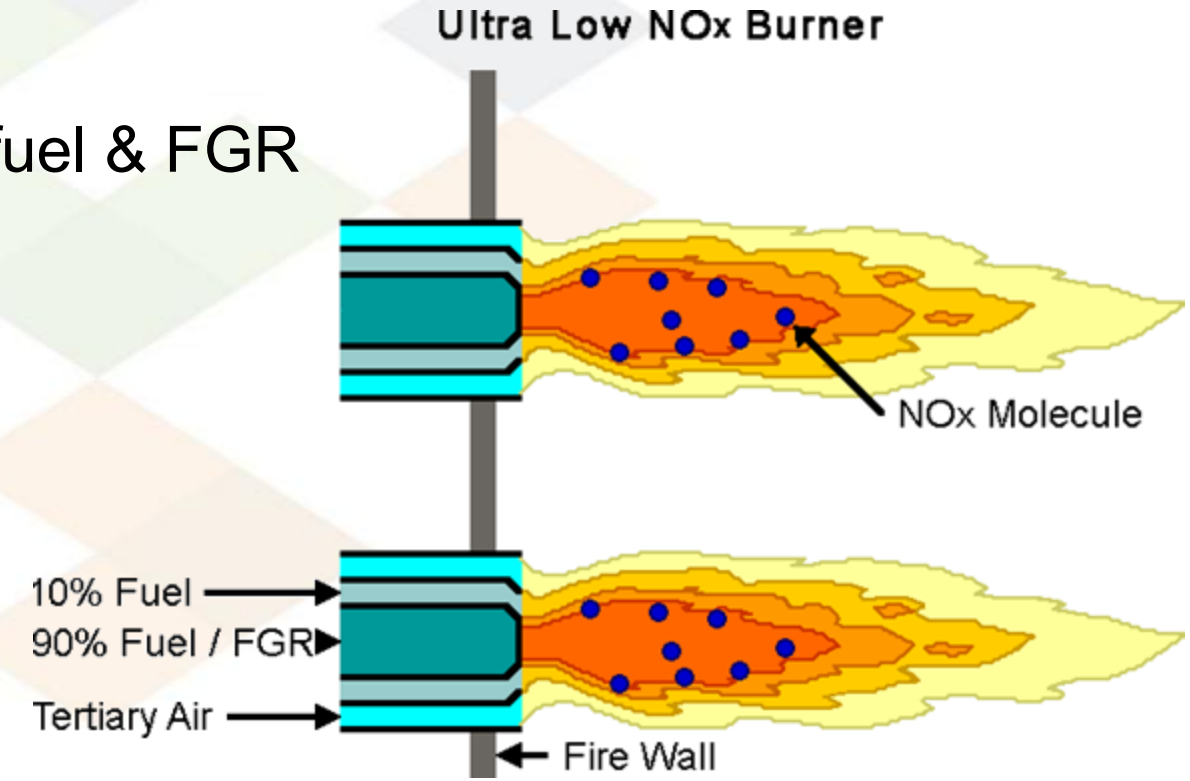
1. Primary air and fuel
   - Rich burn (LEA) with ~90% of fuel
   - Lower NO_X formation
2. Fuel reburning
   - Lean burn with ~10% of fuel
3. Final combustion
   - Tertiary air w/ no fuel (OFA)



Ultra Low NO_X Burner (ULNB)

- Multistage combustion with flue gas recirculation (FGR) to reduce oxygen for a higher rich burn primary zone

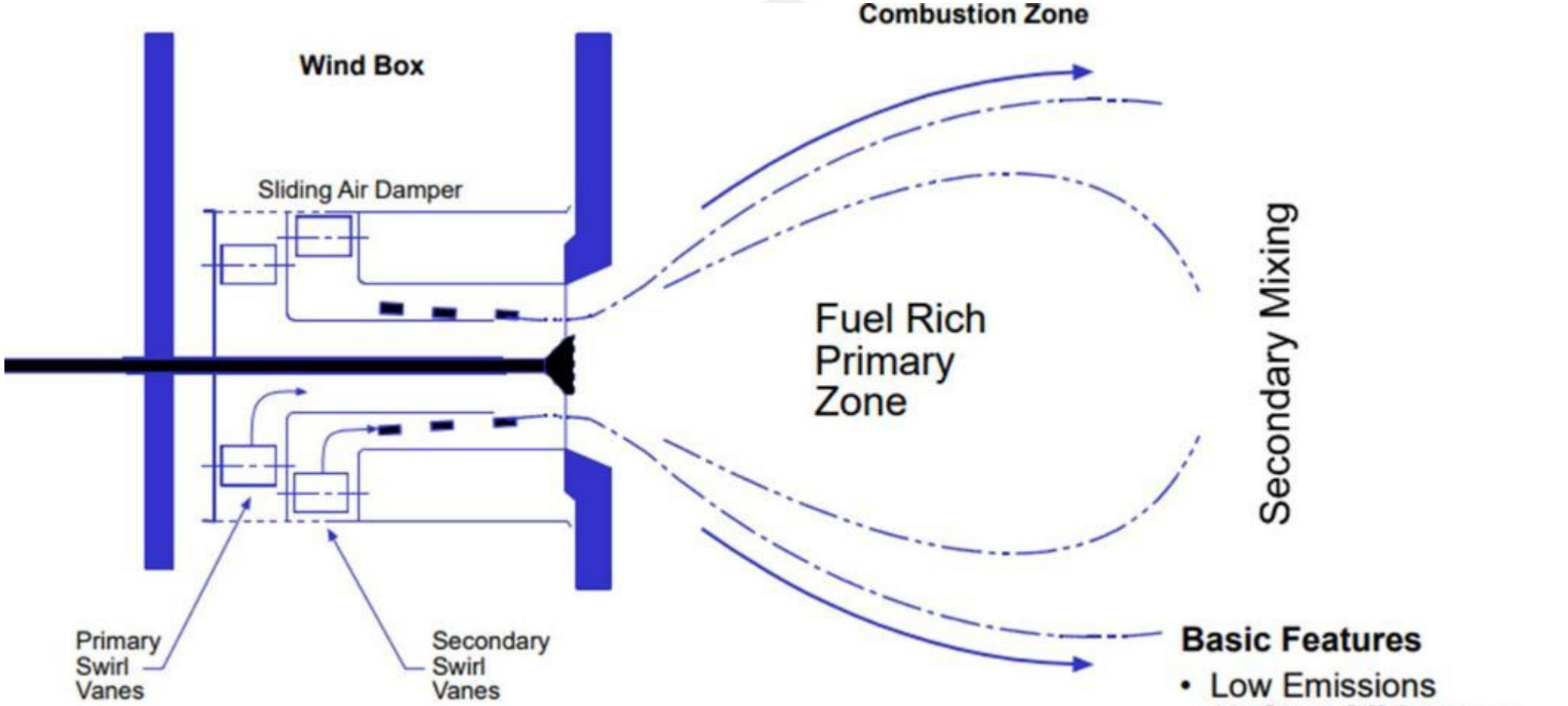
1. Primary air and fuel
   - Rich burn (LEA) with ~90% of fuel & FGR
   - Lower NO_X formation
2. Fuel reburning
   - Lean burn with ~10% of fuel
3. Final combustion
   - Tertiary air w/ no fuel (OFA)



LNB/ULNB

- Staged mixing of fuel and air or FGR within flame at burner
  - Separate zones for air to fuel mixing and stratified combustion
  - Fuel is burned a little in each zone, rather than combusted all at once in one zone
- ULNB requires:
  - Separate air flow rate and swirl dampers
  - Precise air flow control (AFR)

Chapter 7: NO_X Controls
Prevention Controls



Basic Features

- Low Emissions
- Air Shut Off Damper
- Fixed Swirl Vanes
- Fixed Burner Geometry

LNB

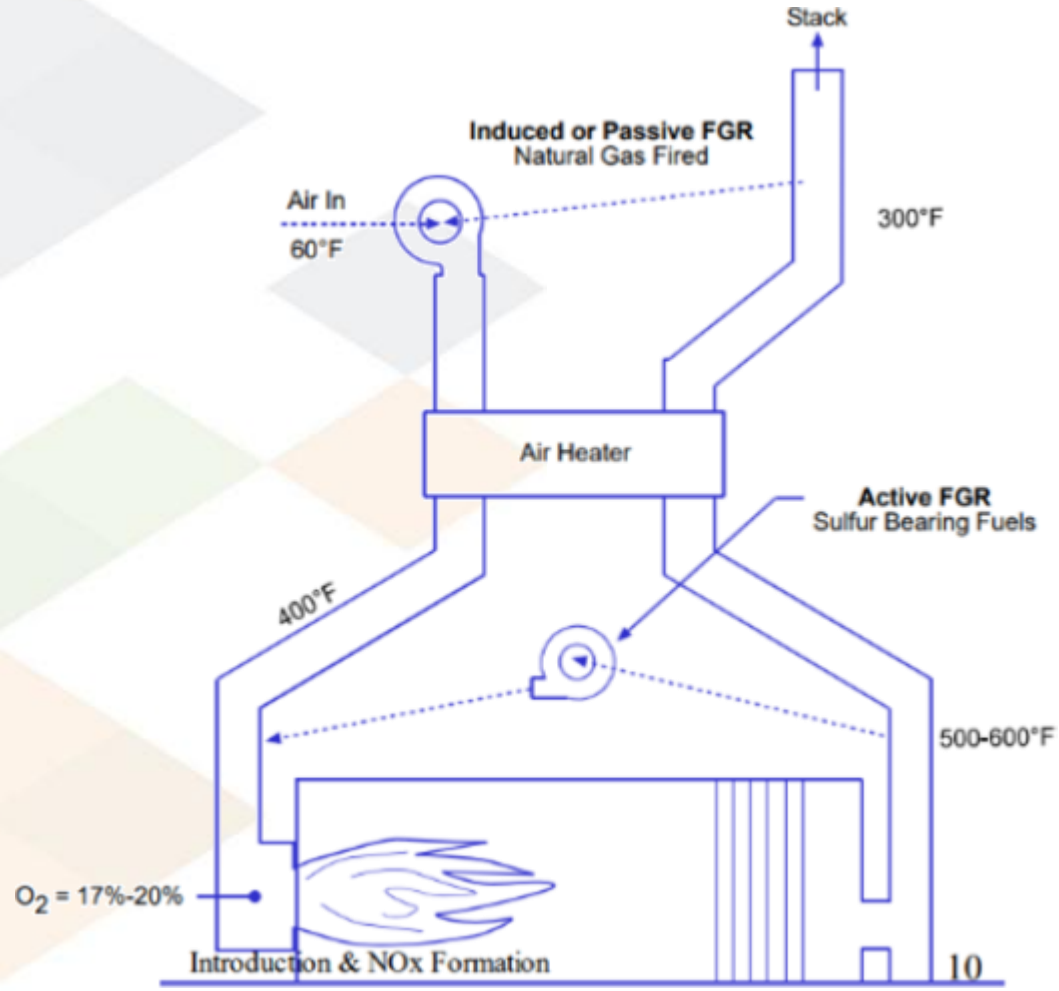


LNB



FGR

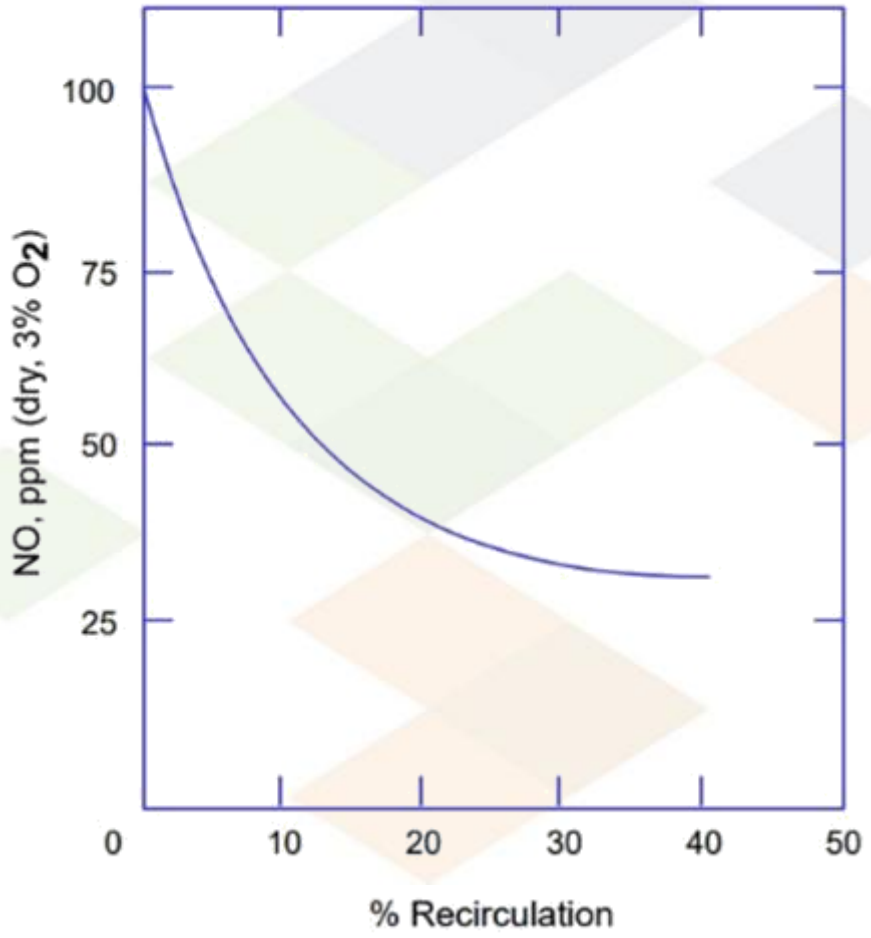
- Flue gas has a lower oxygen content than air and higher concentration of pollutants
- FGR works as a diluent (inert gas) to reduce NO_X
  - Lower heat capacity and oxygen content than air



FGR

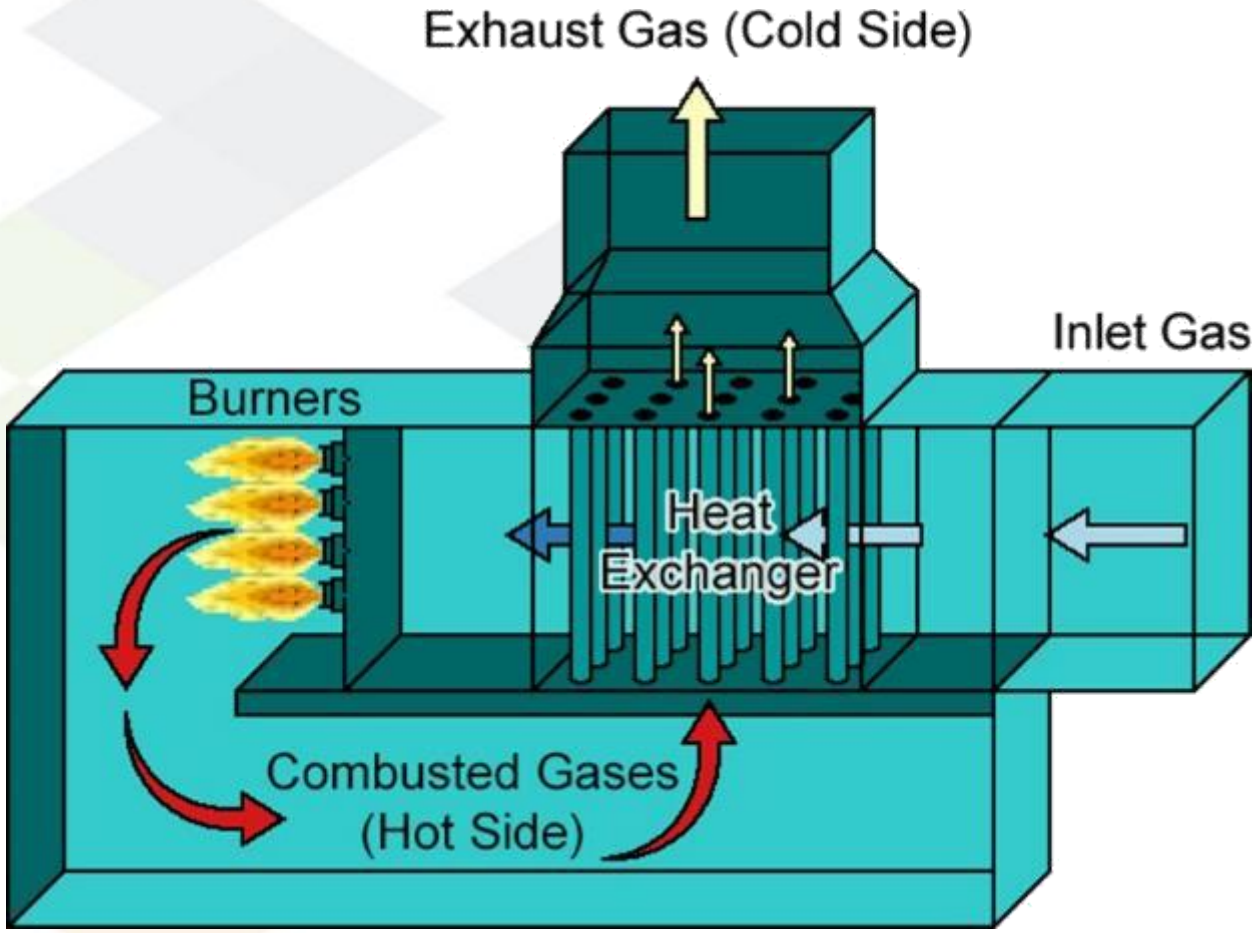


NO Concentration as %FGR



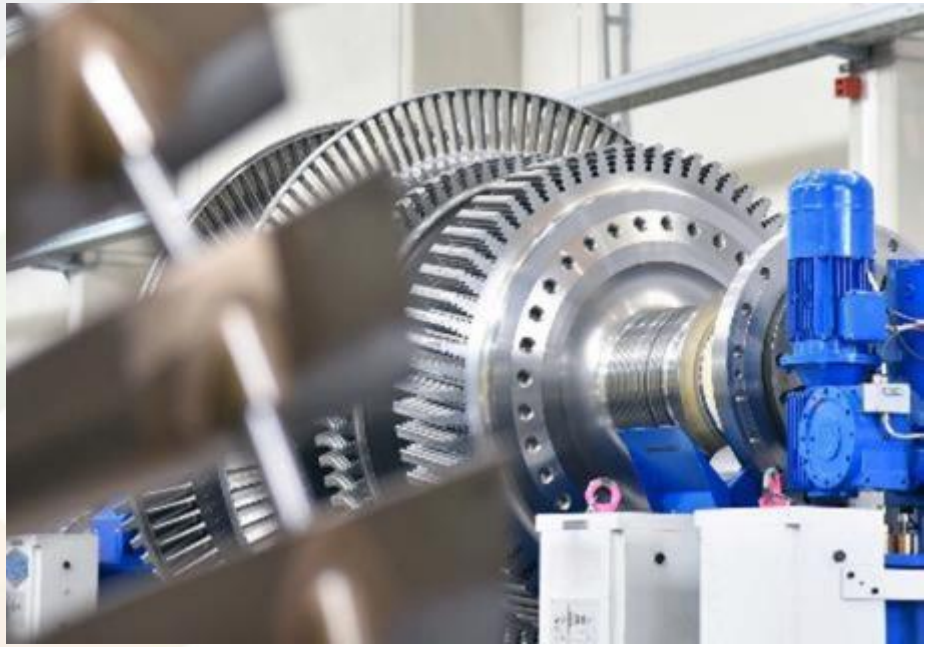
Pre-Heater

- Heat exchangers / pre-heaters are incorporated into combustion units
  - Hot exhaust gases pre-heat inlet gas (combustion air), increasing flame temperature and thermal NO_X
  - Reduces overall fuel consumption (less heat required)



Catalytic Scrubbing

- Reduced flame temperature to prevent NO_X formation
  1. Lean burn pre-burn preheats air
  2. Fuel injection
  3. Catalyst
  4. Burnout – self-ignition below NO_X formation temperatures
- Mostly used in gas turbines
  - Ultra-low NO_X (<2.5 ppm)



Combined Systems

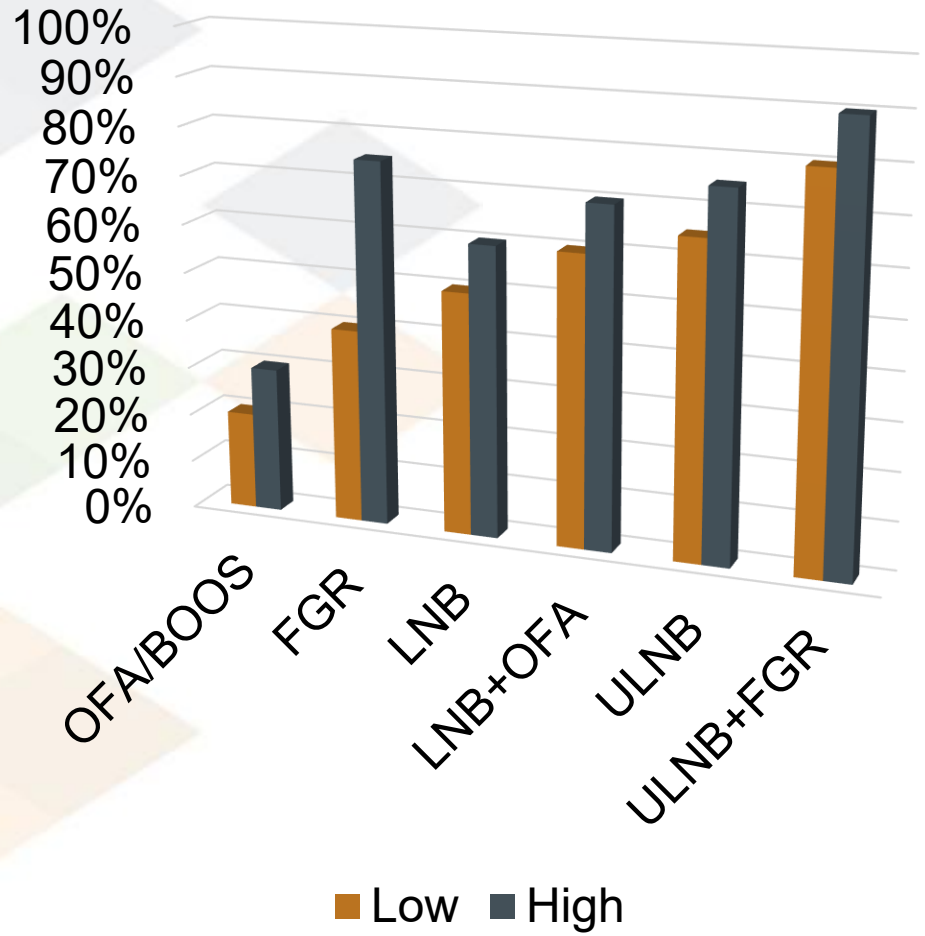
- Low-NO_X systems can combine multiple strategies



Low NOx Burner

Control Efficiency

- OFA and FGR can be combined with LNB/ULNB to reduce NO_X emissions further
- Further NO_X reductions can only occur with add-on controls



Steam / Water Injection

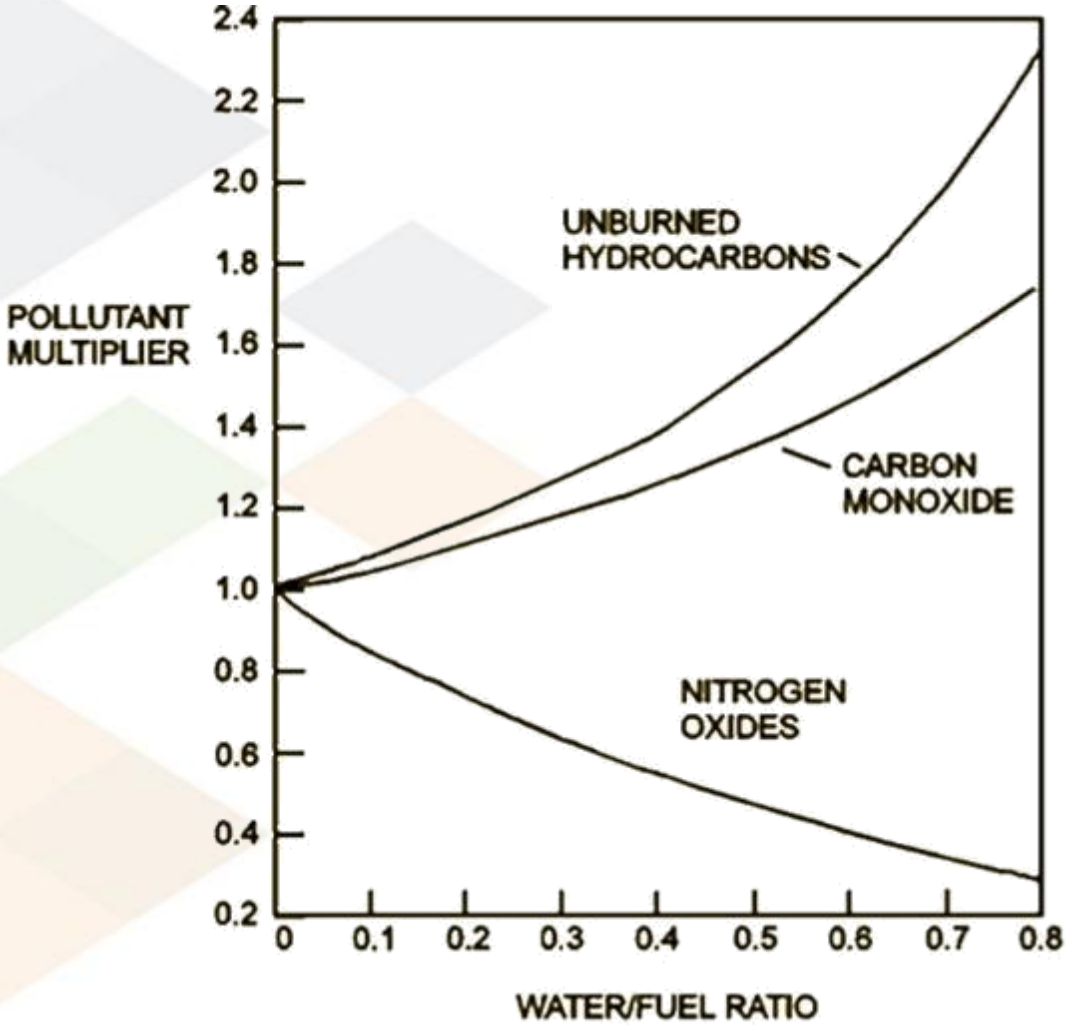
- Water or steam is injected into flame area (combustion chamber of a turbine or heater) to reduce NO_X



Absorbs heat Lower flame temperature Reduce thermal NO_X

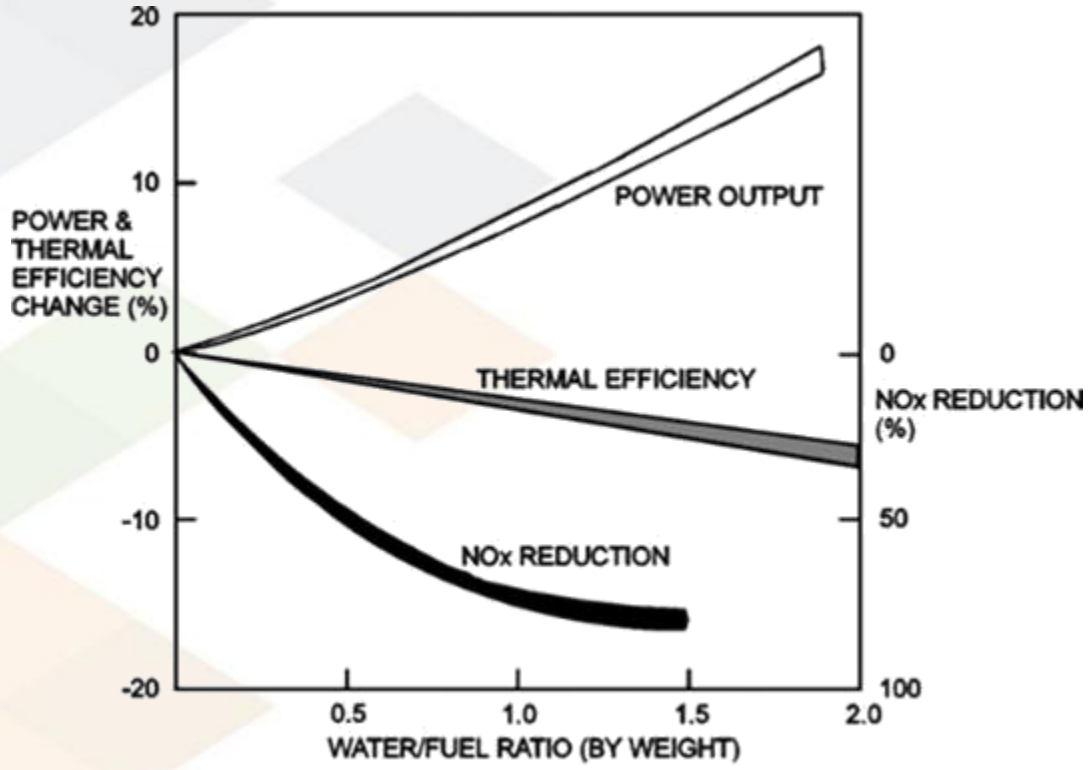
Steam / Water Injection

- Cooling effect of water / steam addition decreases NO_X but increases CO and PIC (VOC)
  - At a certain level, water will extinguish the flame
  - CO and PIC (VOC) increase with higher water dilution rates
- Used in engines and turbines

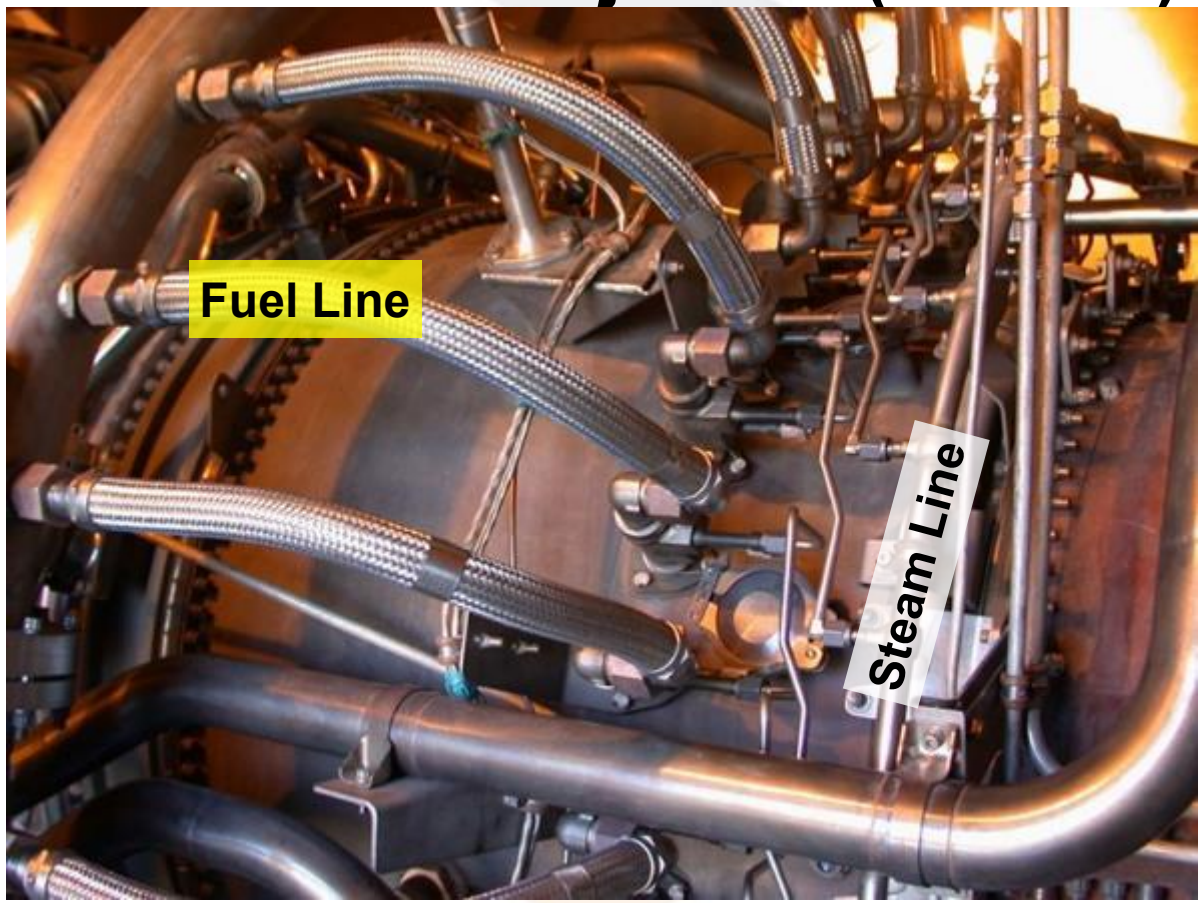


Steam / Water Injection

- Rate of water/steam injection impacts thermal efficiency and turbine power
  - Water/steam injection increases mass flow rate through turbine blades
  - Water/steam injection decreases thermal efficiency of turbine



Water / Steam Injection (Turbine)



LEA

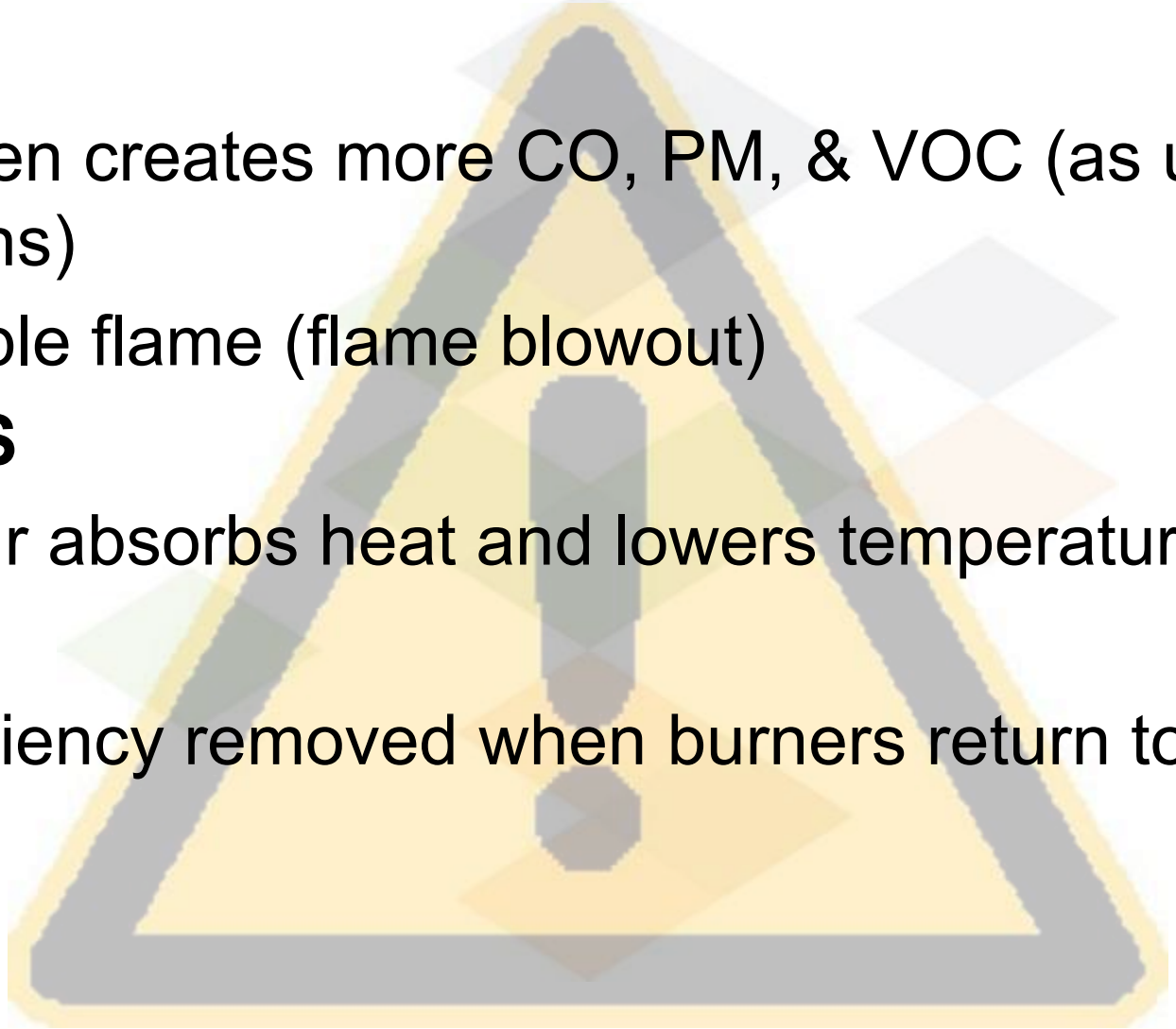
- Lower oxygen creates more CO, PM, & VOC (as unburned hydrocarbons)
- More unstable flame (flame blowout)

OFA & BOOS

- Too much air absorbs heat and lowers temperature

BOOS

- Control efficiency removed when burners return to service



Fuel Staging / LNB / ULNB

- Secondary flame (OFA) relies upon primary flame (LEA) remaining ignited (flame blowout)

Flue Gas Recirculation (FGR)

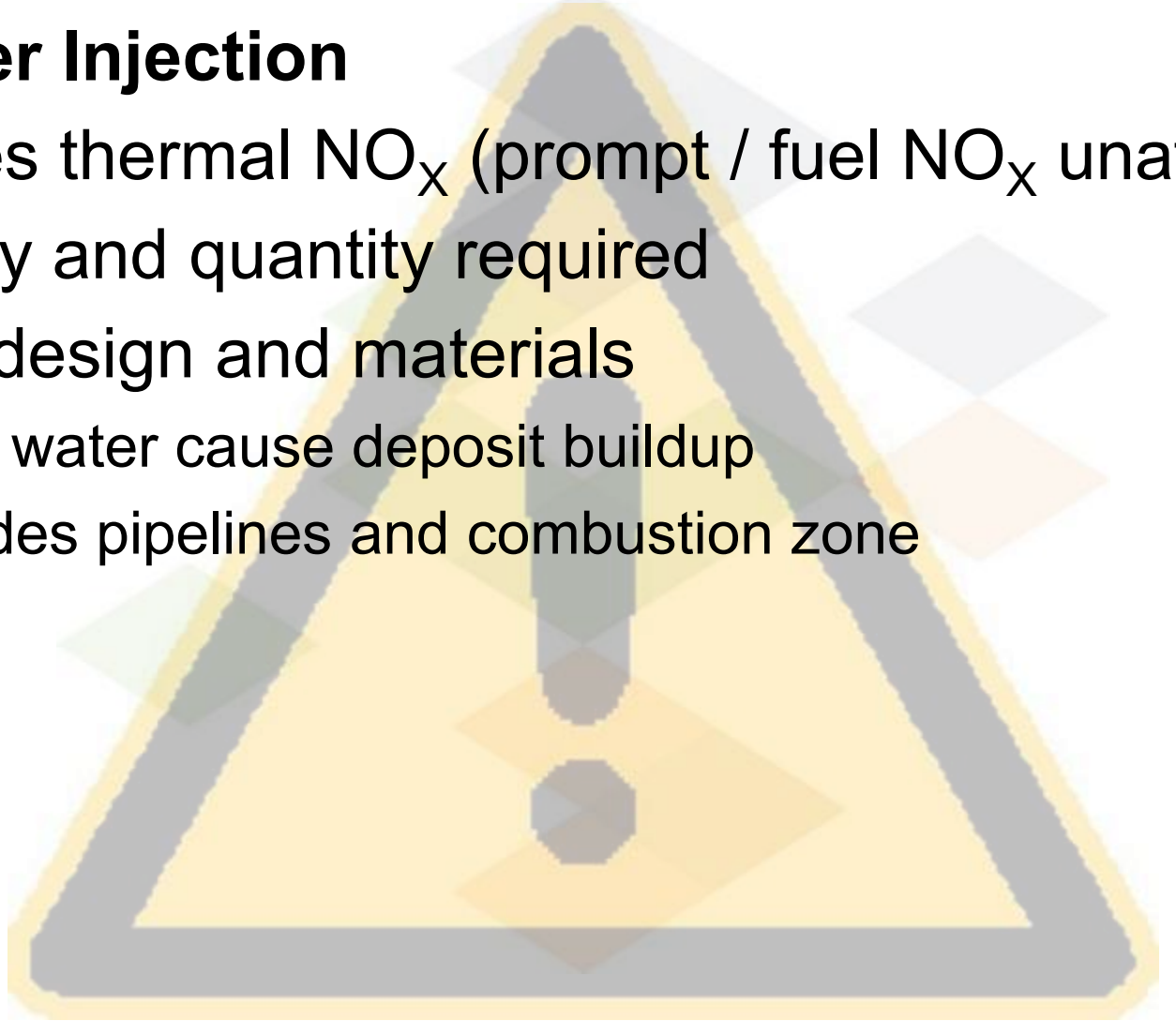
- Lower oxygen creates more unburned hydrocarbons (CO, PM, & VOC)
- More unstable flame (flame blowout)
- Condensation of acid gases in flue gas

All

- More complicated systems have more parts subject to wear

Steam / Water Injection

- Only reduces thermal NO_X (prompt / fuel NO_X unaffected)
- Water quality and quantity required
- Combustor design and materials
  - Impurities in water cause deposit buildup
  - Water corrodes pipelines and combustion zone



NO_X Destruction Controls

- NO_X reduction by reagent
  - Chemical reduction of NO_X to N_2
  - Uses ammonia or urea to remove oxygen from NO_X
  - Requires high temperatures
- Three NO_X destruction controls:
  1. Selective Non-Catalytic Reduction
  2. Selective Catalytic Reduction
  3. Non-Selective Catalytic Reduction



Chapter 7: NO_X Controls
Destruction Controls

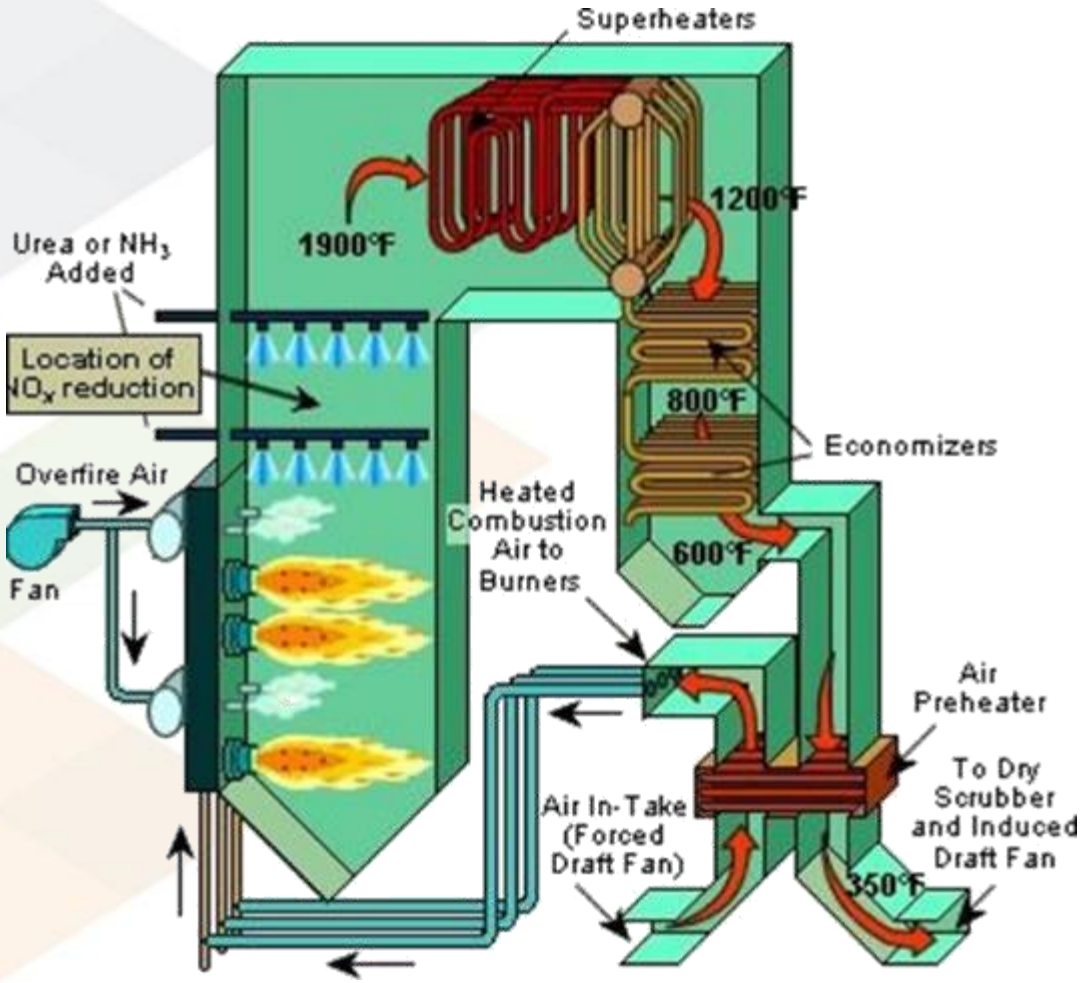
Parameter	Ammonia	Urea
Injection Form	High Vapor Pressure Liquid Ammonia/Water Solution	Liquid Solution
Safety Concerns	Ammonia: Toxic (lungs, eyes) and corrosive	Limited Safety Concerns
Material Storage	Anhydrous: Pressure Vessel Aqueous: Atmospheric Tanks	Atmospheric Tanks (may crystalize at low temperatures)
Injectors	Needs Carrier Gas	Atomizer (Pressure or Twin Fluid)
Temperature	Peak Removal @ 1,750° F	Peak Removal @ 1,850° F Large Dilute Drops Shield Urea
System Complexity	Relatively Simple	Relatively Simple

Selective Non-Catalytic Reduction (SNCR)

- NO_X removed by mixing exhaust gas with liquid ammonia or urea
  - Urea generates chemical intermediates and byproducts
- No catalyst needed

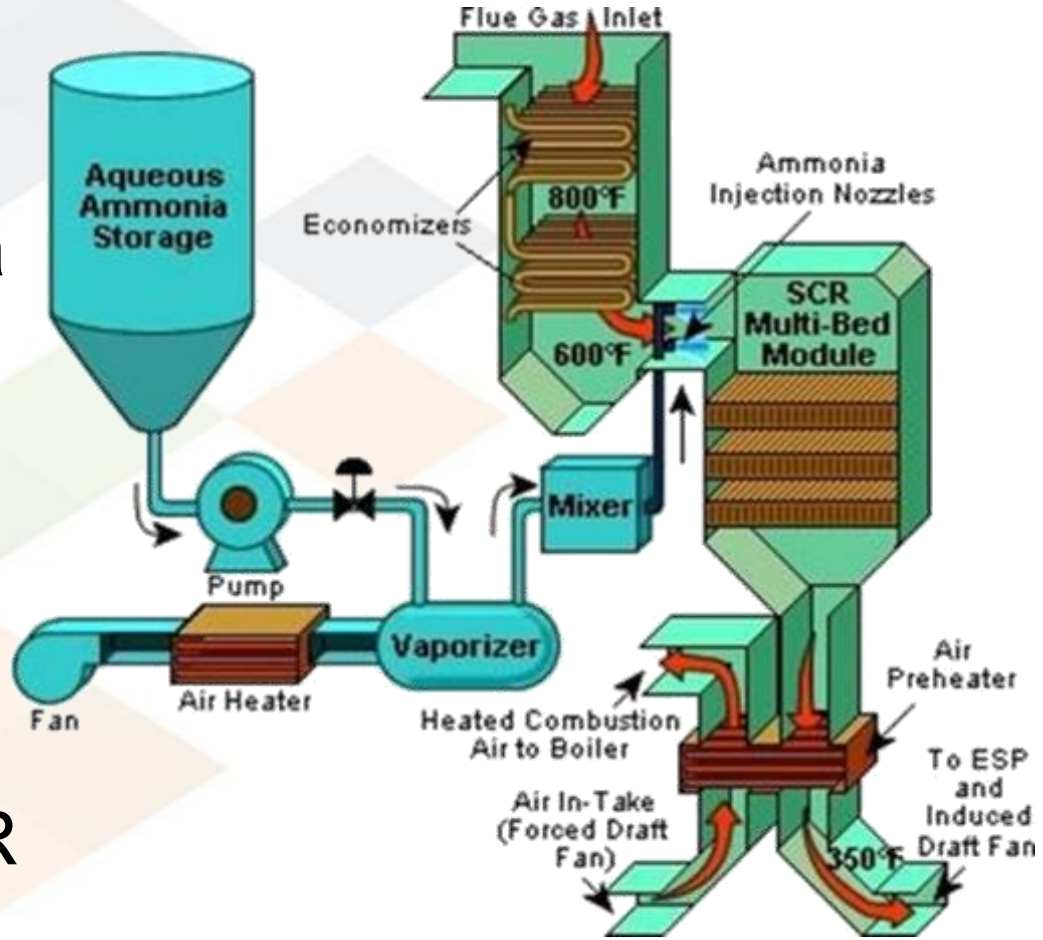
$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

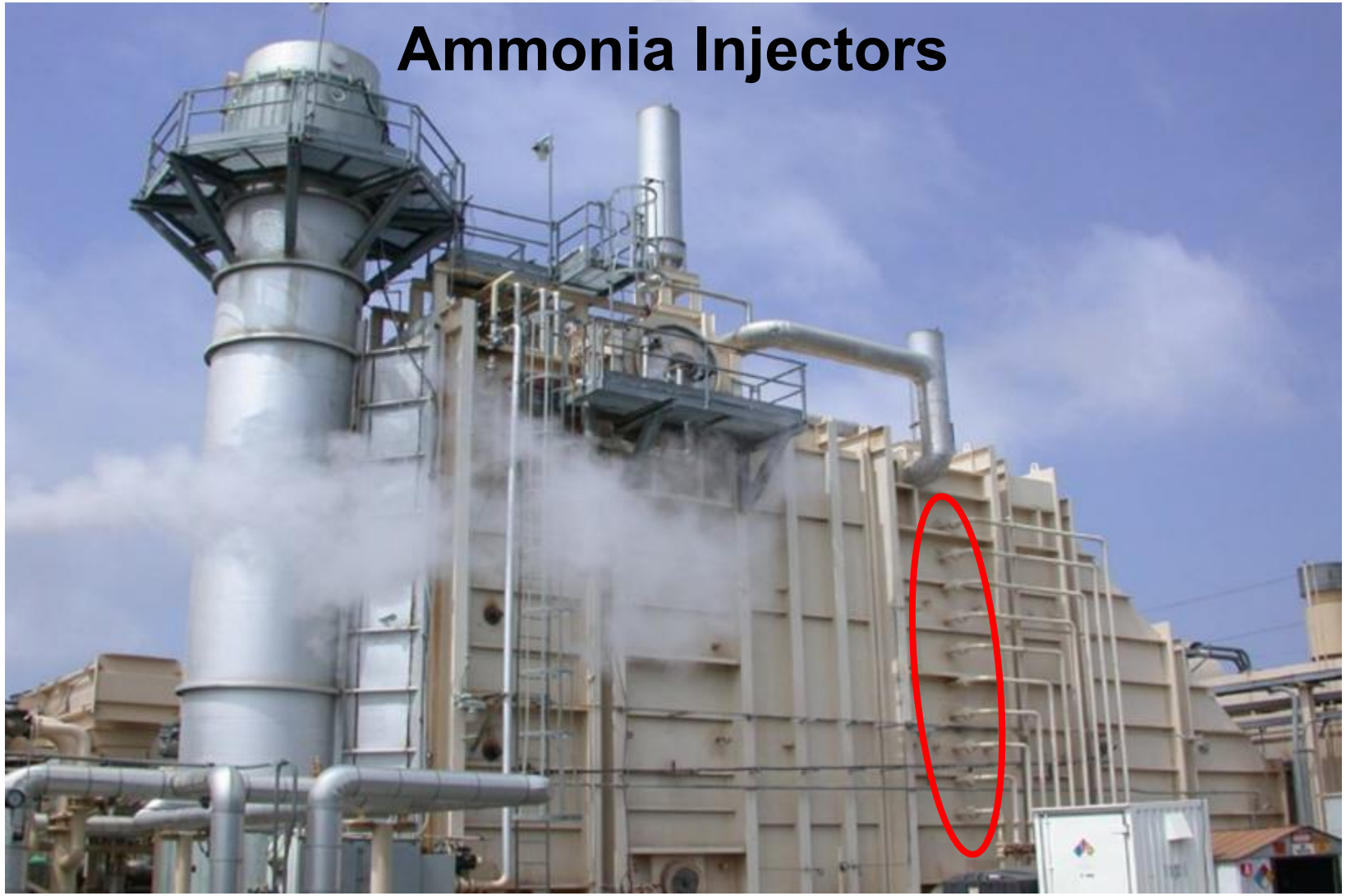


Selective Catalytic Reduction (SCR)

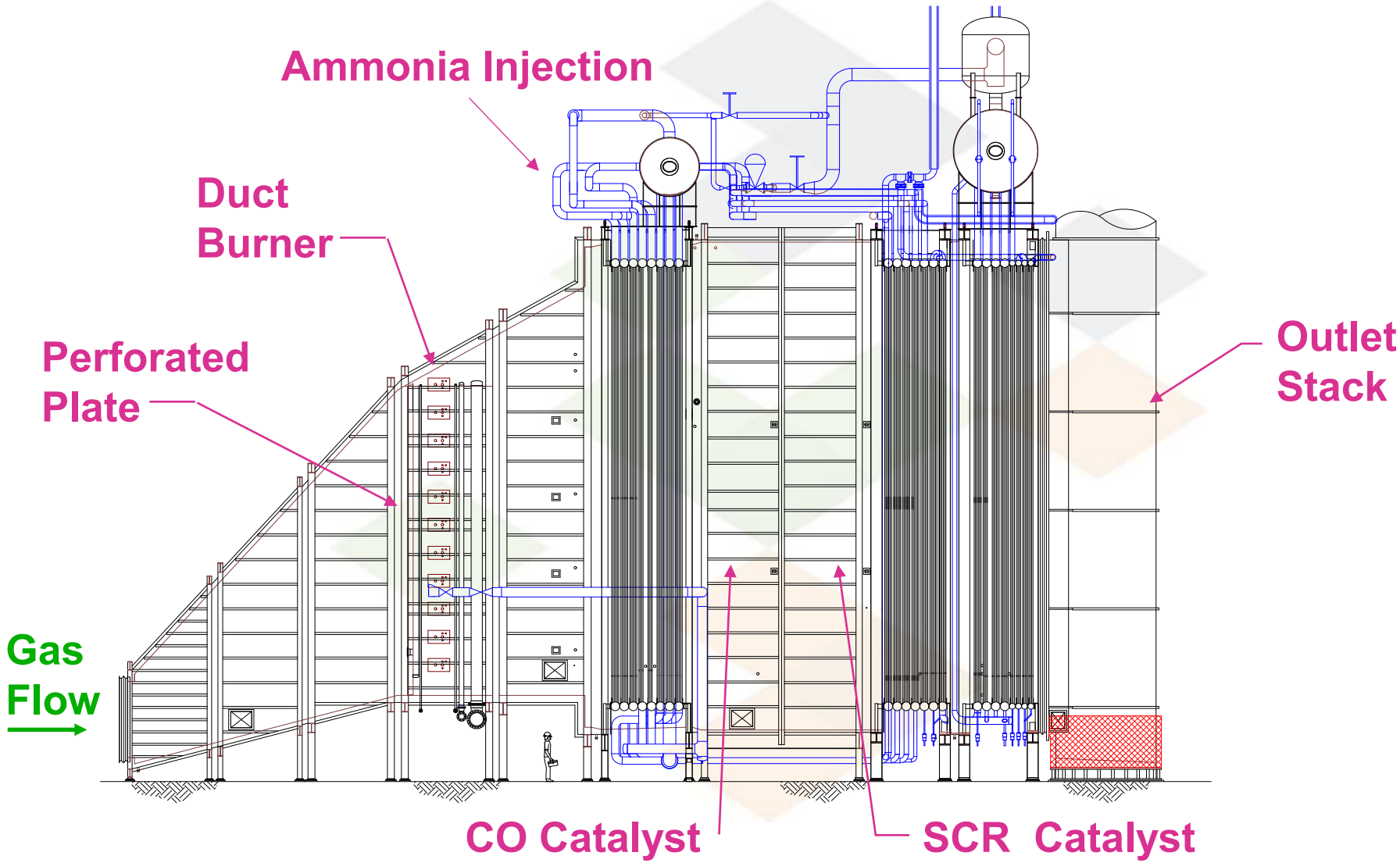
- NO_X is removed by mixing exhaust gas with liquid ammonia or urea in presence of catalyst
- Catalyst causes NO_X reduction to occur faster
- Less ammonia used
  - Less ammonia slip
- Better NO_X reduction than SNCR



Chapter 7: NO_X Controls
Destruction Controls

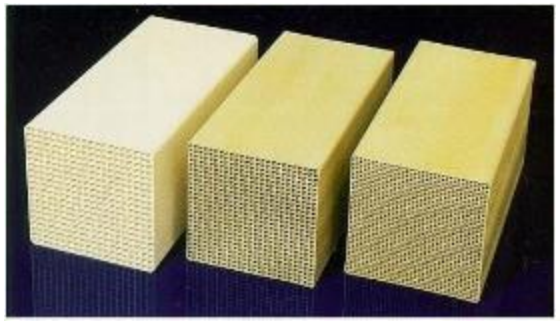


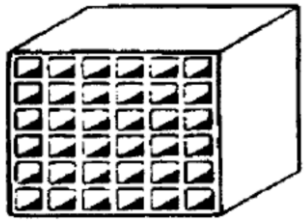
Chapter 7: NO_X Controls
Destruction Controls



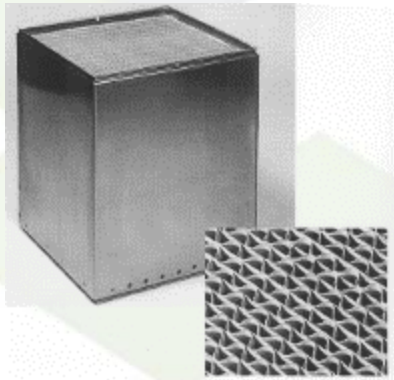
Catalyst Support Types

Extruded Ceramic Honeycomb





Corrugated (Haldor-Topsoe)

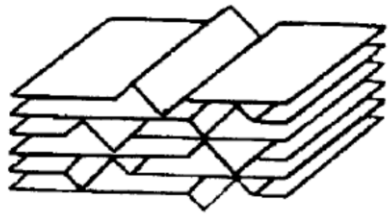


Typical Catalysts:

- Vanadium Pentoxide (V_2O_5)
- Titanium Dioxide (TiO_2)
- Molybdenum
- Tungsten

Plate



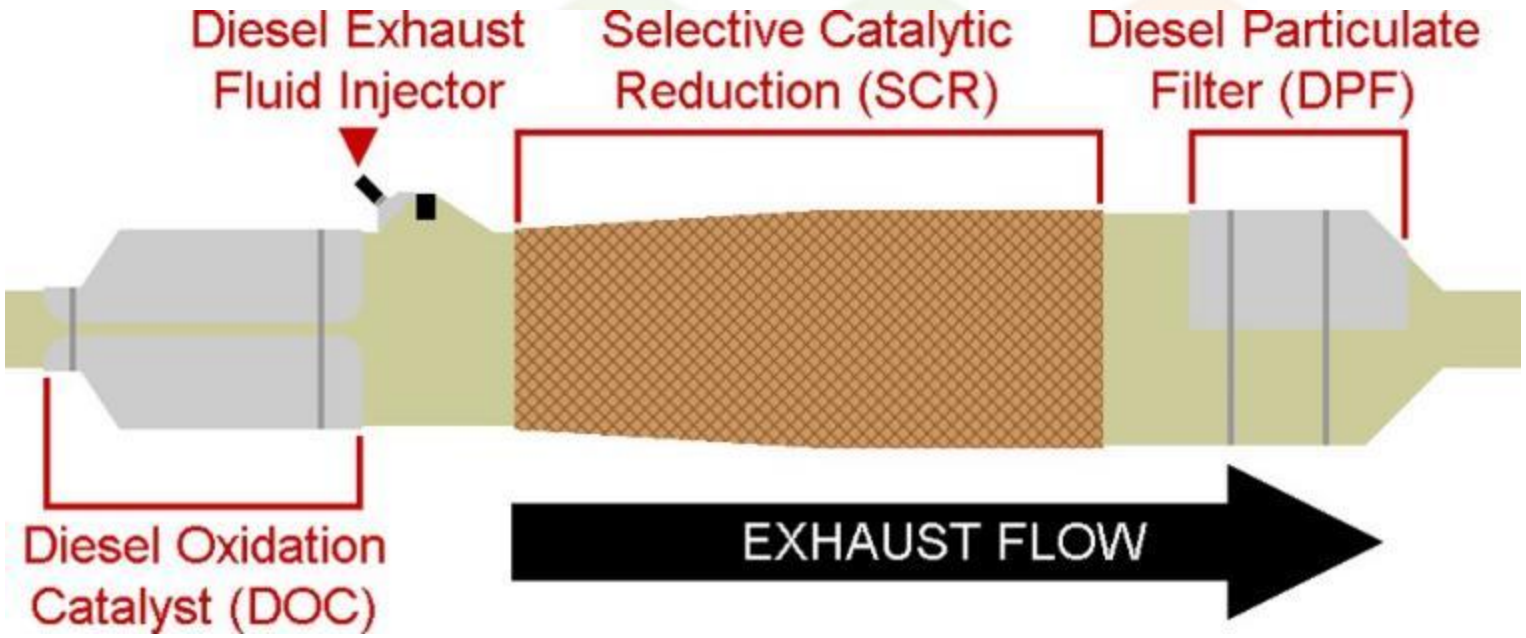


Chapter 7: NO_X Controls
Destruction Controls



Diesel Exhaust Fluid (DEF) & SCR

- DEF is aqueous urea added to diesel engines for NO_X control
  - Diesel engines are usually lean burn, with excess air generating NO_X
- DEF / SCR part of the “Diesel Catalytic Converter”



Chapter 7: NO_X Controls
Destruction Controls

DEF



SCR (Mobile Engine)

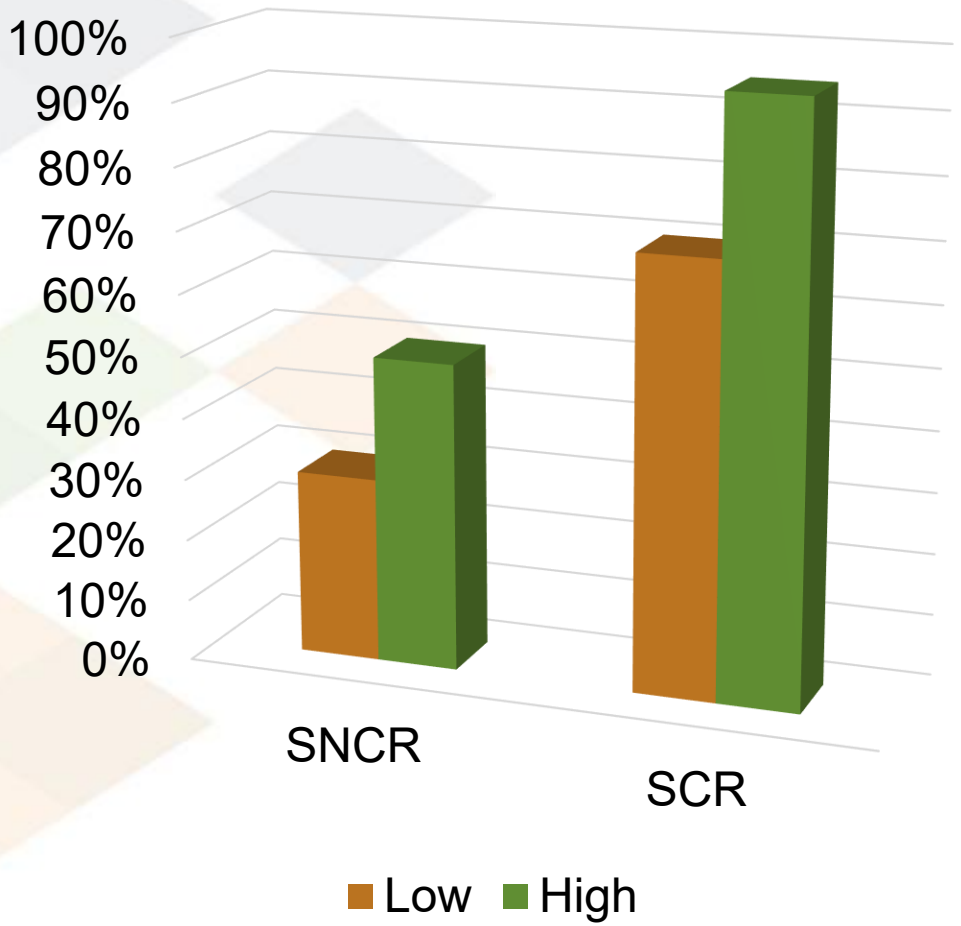


Chapter 7: NO_X Controls
Video

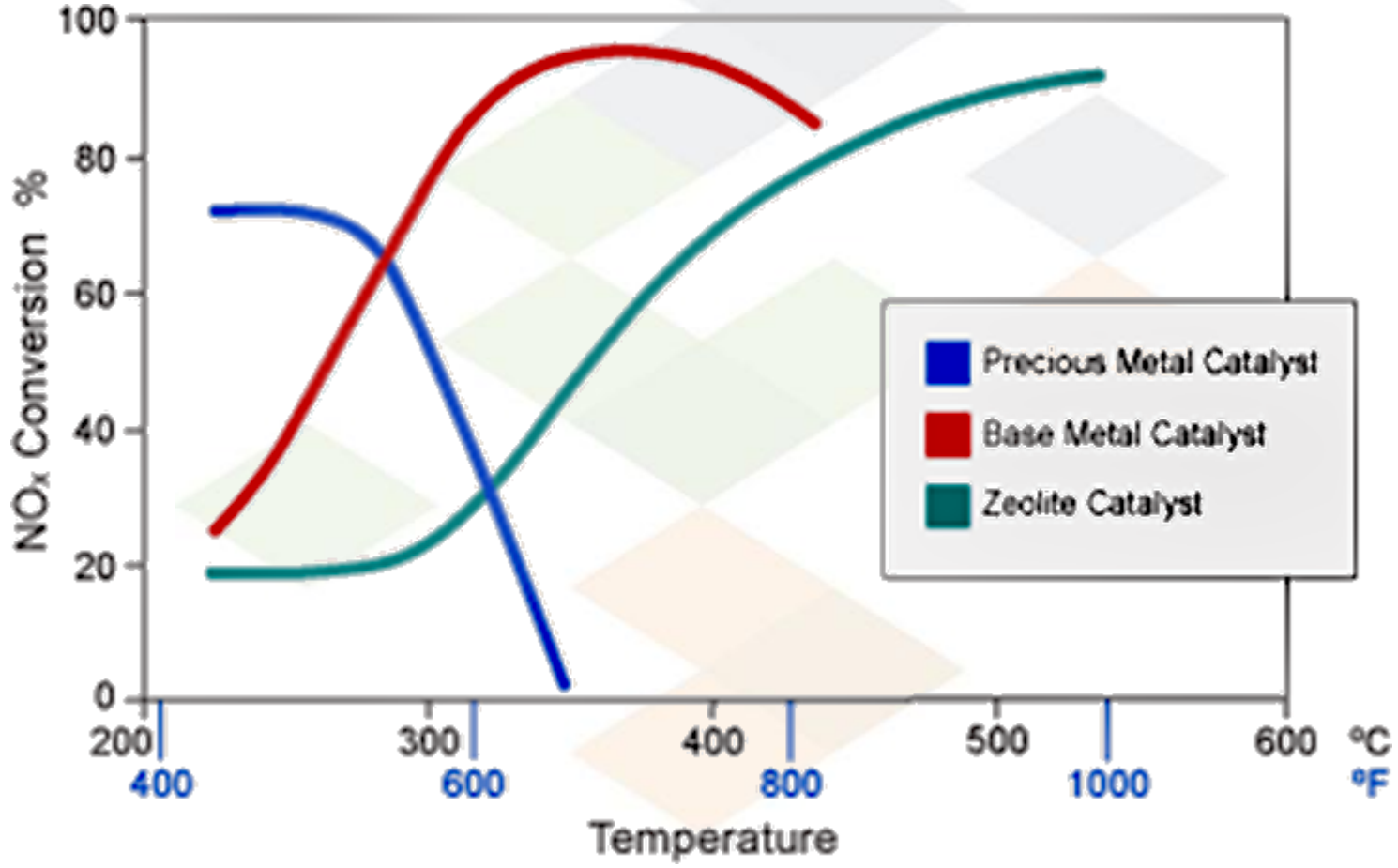
5.1 - SCR.wmv

Control Efficiency

- SNCR: 30-50%
- SCR: 70-95%
  - Control efficiency varies on NO_X concentration, temperature, and catalyst condition

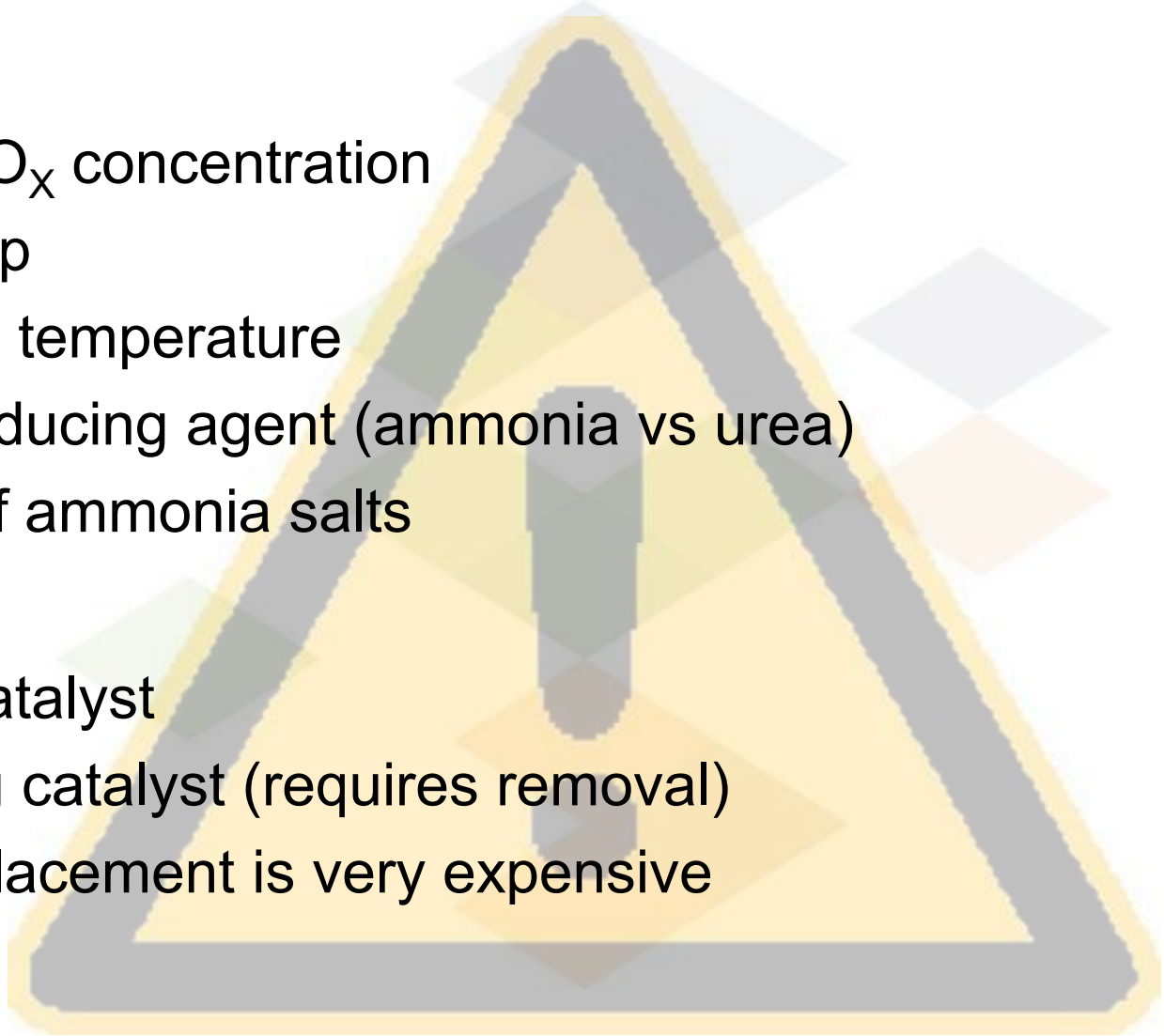


SCR Catalyst Control Efficiencies



Chapter 7: NO_X Controls
Operating Problems

- **SNCR/SCR**
  - High inlet NO_X concentration
  - Ammonia slip
  - Exhaust gas temperature
  - Chemical reducing agent (ammonia vs urea)
  - Formation of ammonia salts
- **SCR**
  - Fouling of catalyst
  - PM covering catalyst (requires removal)
  - Catalyst replacement is very expensive



Ammonia Slip

- Lower temperature increases slip and salt formation
- Higher temperature increases oxidation
  - SCR at 500-800ºF
  - SNCR at 1,600-2,100°F
- Monitor ammonia loading rate
- Ammonia positively impacts particle resistivity in ESPs



Chapter 7: NO_X Controls
Operating Problems

PM Removal: Soot Blower



Uses steam / compressed air to clean catalyst

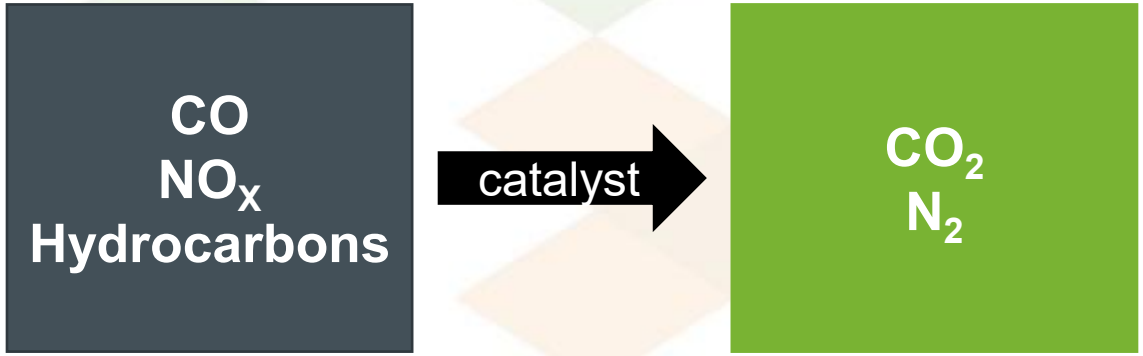
PM Removal: Sonic Horn



Uses sound to clean catalyst

Non-Selective Catalytic Reduction (NSCR) or 3-way Catalyst

- In non-selective catalytic reduction, CO, NO_X and hydrocarbons are converted into CO_2 and N_2 via a catalyst
- Catalyst causes CO and NO_X to mutually annihilate each other
- Does not need additional reagents (ammonia / urea)



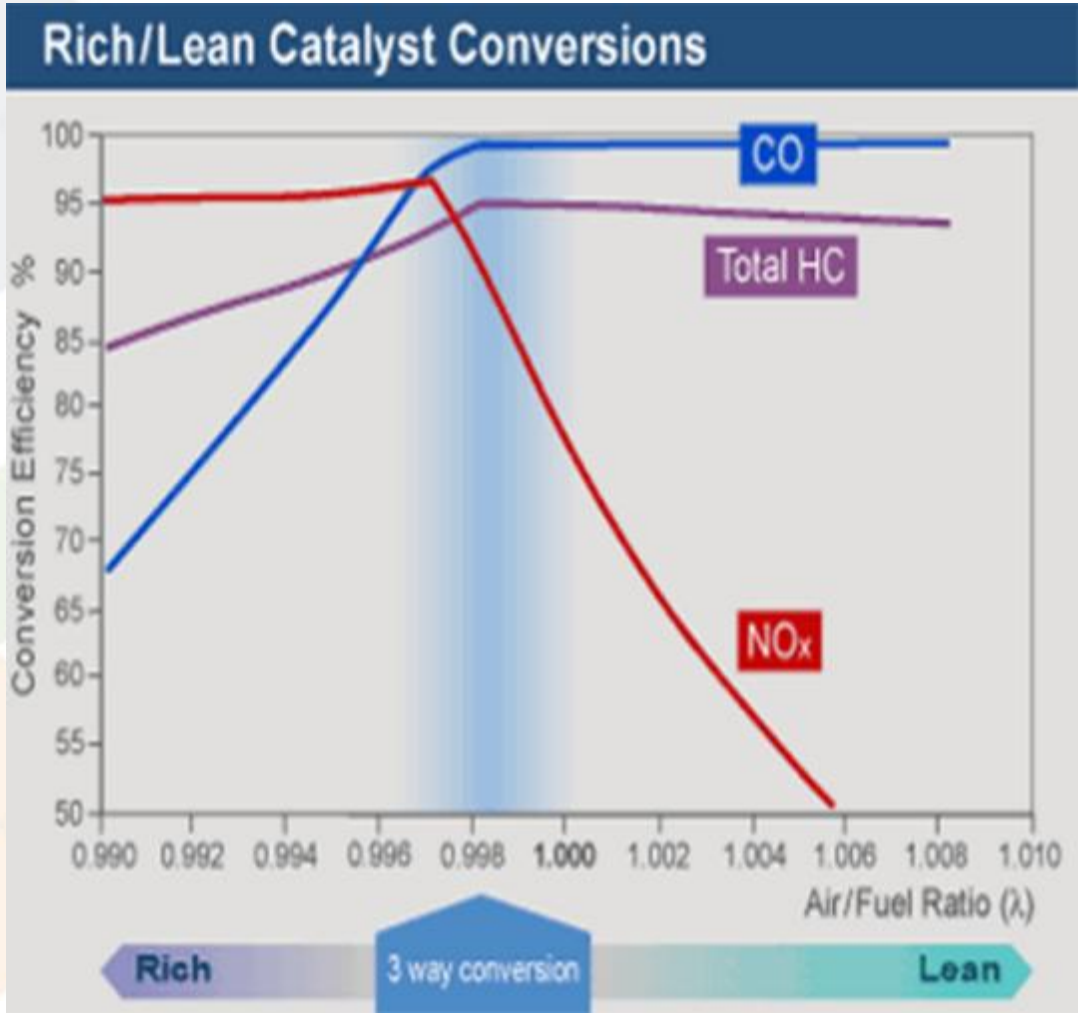
NSCR / 3-Way Catalyst

- Primarily used in Rich Burn engines (fuel rich / lean air)

  $2CO+2NO \rightarrow 2CO_2+N_2$

  $2NO+CH_4+O_2 \rightarrow N_2+CO_2+2H_2O$

- Provides up to 98% control for CO and NO_X

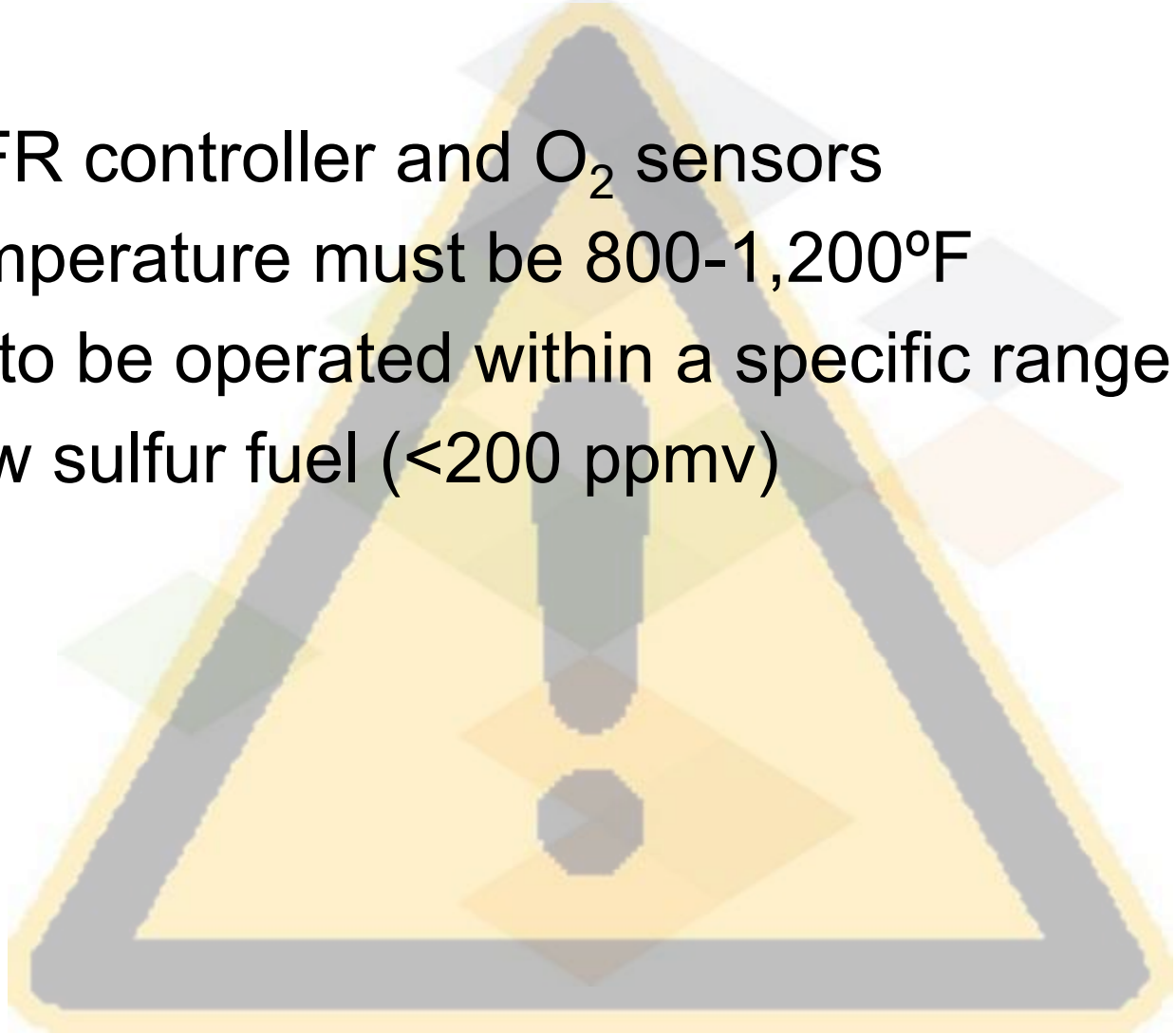


NSCR / 3-way Catalyst



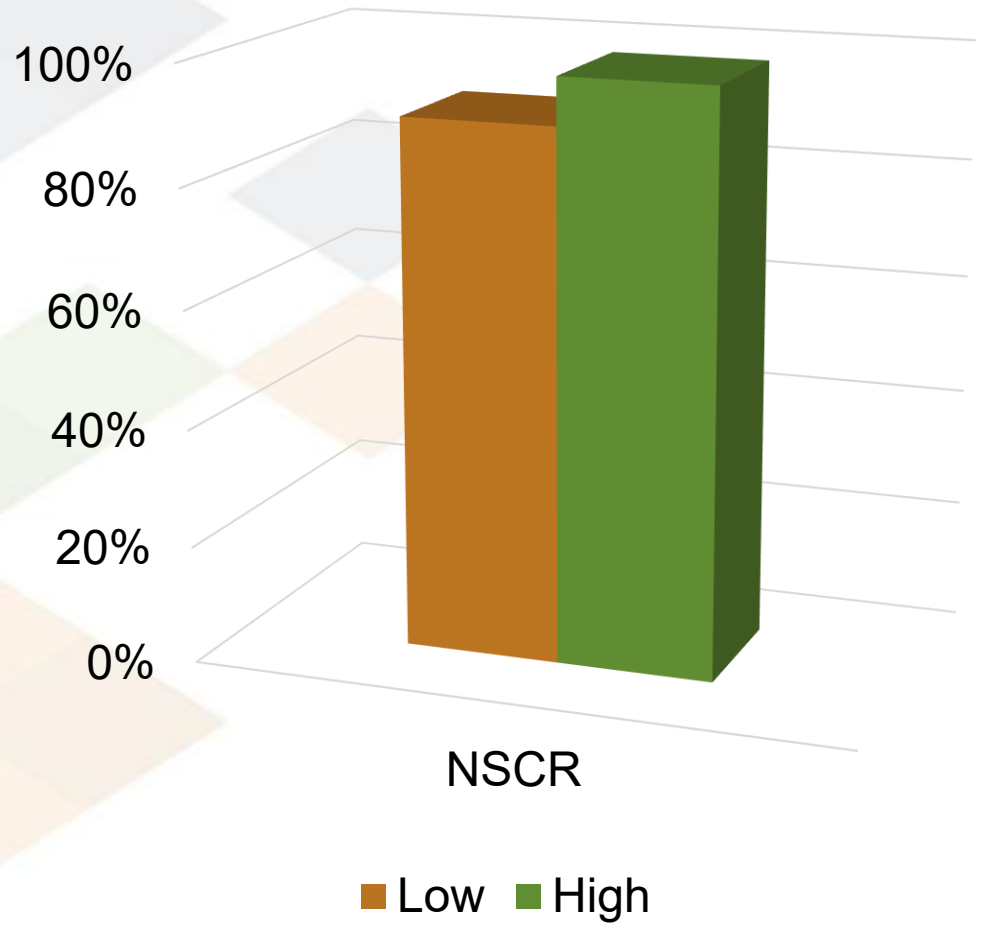
NSCR/SCR

- Requires AFR controller and O_2 sensors
- Inlet gas temperature must be 800-1,200ºF
- Engine has to be operated within a specific range
- Requires low sulfur fuel (<200 ppmv)



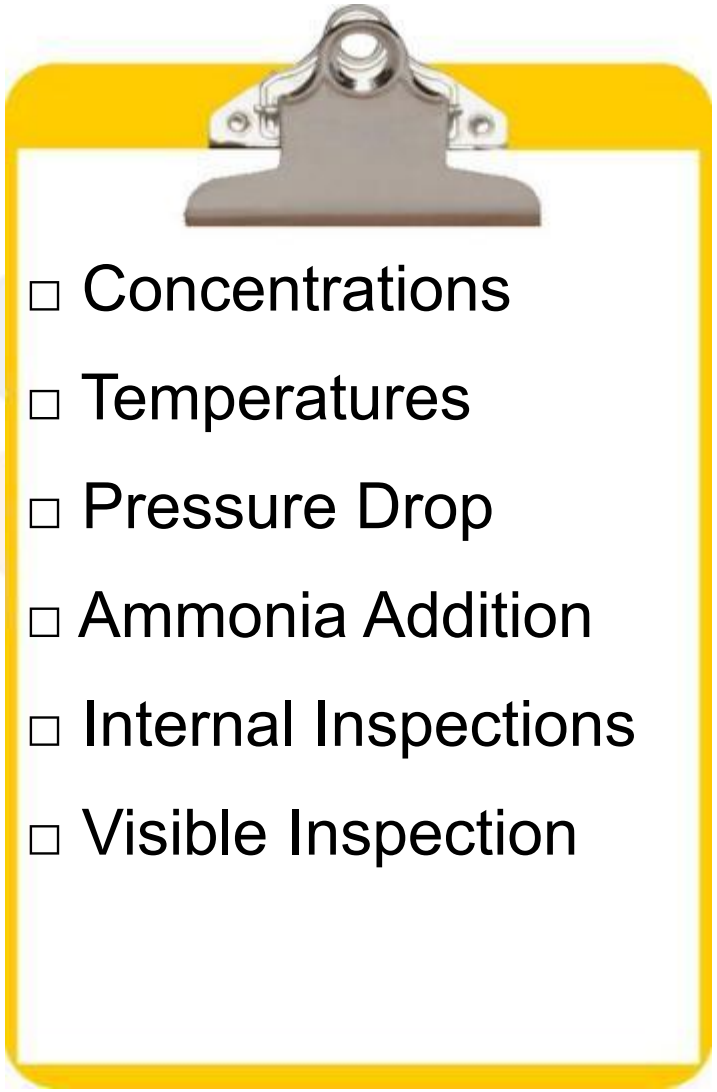
Control Efficiency

- NSCR: 90-98%
  - Control efficiency varies on pollutant concentration, temperature, and catalyst condition



Inspection Parameters

- NH_3 addition (SNCR & SCR)
  - Ammonia slip
- O_2 concentration (FGR)
- Temperature
  - Ammonia / urea addition (SNCR & SCR)
  - Catalyst bed (SCR & NSCR)
- Catalyst bed pressure differential
- Internal inspection



Chapter 7: NO_X Controls
Recap

In this chapter, we discussed:

- How NO_X control technologies operate
- Common types of NO_X control technologies
- Key design considerations for NO_X control technologies
- Typical achievable control efficiencies
- Monitoring methods for NO_X control technologies
- Common problems with NO_X control technologies
- Ensuring compliance